DTIC FILE COPY

3

ETL-0540

AD-A212 622

An Analysis of Air Photo and Radar Imagery of Barro Colorado Island, Panama

J. N. Rinker
P. A. Corl

July 1989

Approved for public release; distribution is unlimited.

U.S. Army Corps of Engineers
Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060-5546

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for Public Release; Distribution is Unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): ETL-0540

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: U.S. Army Engineer Topographic Laboratories

6b. OFFICE SYMBOL (If applicable): CEETL-RI-CRS

6c. ADDRESS (City, State, and ZIP Code): Fort Belvoir, Virginia 22060-5546

7a. NAME OF MONITORING ORGANIZATION:

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING / SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

8c. ADDRESS (City, State, and ZIP Code):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
4A161102			

11. TITLE (Include Security Classification): An Analysis of Air Photo and Radar Imagery of Barro Colorado Island, Panama

12. PERSONAL AUTHOR(S): J. N. Rinker and P. A. Corl

13a. TYPE OF REPORT: Research Report

13b. TIME COVERED: FROM 1979 TO 1981

14. DATE OF REPORT (Year, Month, Day): 1989, July

15. PAGE COUNT: 60

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Air photo analysis, radar analysis, closed tree canopy, tropical landforms.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Imagery of terrain that is covered with a closed canopy of tall trees does not show the ground surface, and any information about surface characteristics, such as rock and soil types, structure, drainageways, etc., must come from an examination of the tree canopy surface. An evaluation of stereo aerial photography showed that inferences could be made about general terrain characteristics such as landform, probable structure and rock types, and major drainageways, but it requires experienced and skilled analysts, and stereo imagery. Surface roughness, obstacles, and minor drainageways could not be determined. Lack of vegetation penetration by radar severely limits the quantity and quality of information that can be derived.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: E. James Books

22b. TELEPHONE (Include Area Code): (202) 355-2774

22c. OFFICE SYMBOL: CEETL-IM-T

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Illustrations

Tables

PREFACE

This study was conducted under DA Project 4A161102B52C, Task 0C, WU 010, "Indicators of Terrain Conditions."

The study was performed during the period 1979 to 1981 under the supervision of Dr. Jack N. Rinker, Team Leader, Center for Remote Sensing, and Mr. Lawrence A. Gambino, Director, Research Institute, U.S. Army Engineer Topographic Laboratories.

Colonel David F. Maune, EN, was Commander and Director, and Mr. Walter E. Boge was Technical Director of the U.S. Army Engineer Topographic Laboratories during the report preparation.

AN ANALYSIS OF AIR PHOTO AND RADAR IMAGERY OF BARRO COLORADO ISLAND, PANAMA

INTRODUCTION

Background. The manual analysis of stereo aerial photography is a reliable and rapid means for obtaining general information about terrain characteristics in terms of material identities, properties, and conditions within a given area. As a procedure, the analysis is based on a careful examination, in the stereo image, of several pattern elements, i.e., landform, drainage (plan and elevation), erosion, deposition, vegetation, cultural, tone and texture, and special. Wherever there is a change in any one of these patterns, there is a basis for a boundary and the presumption that there has been a corresponding change in the materials, or conditions, that that pattern represents. Landform patterns are related to the physical properties of materials. Drainage patterns are related to permeability, cohesiveness, and ease of erosion. Vegetation patterns are related not only to vegetation types but also to associated changes in rocks, soil texture, soil moisture, etc. Patterns of erosion and deposition can serve as indicators about the physical properties of materials. Cultural patterns are linked to man's activities and to the nature of the landscape. Tone and texture patterns can provide information about soil and rock types, and vegetation communities. Special patterns include joints, faults, slips, etc.[1]

Aside from whatever interest one might have in the vegetation of a region, or in the fact that the vegetation patterns can provide useful corollary information, the vegetal cover can cause problems. As this cover increases, it becomes difficult to get a direct impression of anything more than the general features of shapes, much less note such details as subtle slope changes, gully cross sections and gradients, boundaries between soil units or landform units, etc. In the extreme case of a closed dense tree canopy, which can occur in both temperate and tropical regions, the ground cannot be seen, and any information about it must come by inference and speculation from examining the surface of the tree canopy, which can be tens of meters above the ground. Certainly the overall shape of the canopy surface is related to the shape of the ground beneath it, but it is not exact in its conformance. Yet, the Army needs terrain information in such regions and analyses of such photography must be done. When the analyses are done, however, one faces the same questions about reliability, i.e., how representative of ground conditions is the information that was derived from the photos or other imagery? How good are the predictions about cross-country movement, mobility, location of engineering materials, etc.? Do the predictions about shape, slope, and composition derived by inference from landform and drainage patterns which, in turn, were inferred from shapes within the canopy, hold up when the site is examined on the ground? Of the drainage pattern that exists on the ground, how much of it was traced out on the imagery? 40

[1] For information about the details of the method of air photo analysis used in this study, refer to:

Frost, R.E., 1952. Airphoto Interpretation, Research and Instruction at Purdue. *Photogrammetric Eng.*, September 1952.

Rinker, J.N., and Frost, R.E., 1981. *Remote Sensing for Engineering Site Selection.* Proceedings, Int'l Conf. on Computing in Civil Eng., pp. 359-371, American Society of Civil Engineers, New York, New York, 11-15 May 1981.

Rinker, J.N., and Corl, P.A., 1984. *Air Photo Analysis, Photo Interpretation Logic, and Feature Extraction.* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL-0329, AD-A153 926.

percent? 80 percent? 200 percent? And, if known, how representative is this figure of merit with respect to different vegetation types on different landforms and in different climates? Furthermore, what levels of training, experience, and skill are needed to derive such information? This study is one phase of an effort to gain insight into these problems. It was done, along with other analyses, in conjunction with the preparation of a report on air photo analysis and interpretation logic,[2] and in conjunction with another cooperative project involving the analysis of radar and Landsat imagery of Panama.[3]

Objectives. The objectives are (1) to determine the approximate levels of ground information that can be obtained by an air photo analysis of an area that has a closed canopy of trees, i.e., the ground is not visible in the photos, and auxiliary information is not available; (2) to determine the approximate levels of terrain information in terms of landform, structure, and lineations that can be derived from an analysis of radar imagery of an area with a closed tree canopy; (3) to determine what levels of skills and experience are required to derive the various information elements; and (4) to evaluate the results in relation to stated Army information needs.

SITE LOCATION

The site selected for the study is Barro Colorado Island in Gatun Lake, in the Republic of Panama (see fig. 1). The island is a hilltop isolated from other land units as a result of the creation of the lake during the construction of the Panama Canal. The lake serves as a reservoir for operating the locks. The reasons for choosing this site include (1) it is a good example of a tropical forest with a dense closed tree canopy; (2) it is under the jurisdiction of the Panamanian Government as a Natural Area and thereby has some degree of protection against rapid changes; (3) the Smithsonian Institution maintains a research center on the island (staff and facilities); and, (4) at the time, ETL had other work in Panama in cooperation with the Defense Mapping Agency (DMA), Inter-American Geodetic Survey (IAGS), that involved this site.

IMAGERY TYPES AND SOURCES

Photography. The aerial photography included Ektachrome infrared taken in 1979, and panchromatic taken in 1949. The Ektachrome infrared photography (north-south flightlines) was taken by the Instituto Geografico Nacional "Tommy Guardia" (IGNTG), Panama, and bears the designation PC-AID PANAMA R-4, scale 1:20,000, March 1979. The stereotriplet frames that cover Barro Colorado Island are 000120, 000121, and 000122 of roll L-5. Color prints made from the positive color transparencies were used for mapping landform, drainage, and lineations. The panchromatic photography (east-west flightlines) was taken by the U.S. Army and bears the designation 4RS-7/MISS TM-27, 1 Jan 1949, VT. Frames 36, 37, and 38 cover the island. It has a scale of approximately 1:40,000.

---

[2] Rinker, J.N., and Corl, P.A., 1984. *Air Photo Analysis, Photo Interpretation Logic, and Feature Extraction*. U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL-0329, AD-A153 926.

[3] Stewart, R.H., Stewart, J.L., and Rinker, J.N., 1983. *Use of SLAR, SIR-A, and Landsat Imagery in Interpretation of Geologic Structures and Relations in Panama*. Presented at the Caribbean Geological Congress, Cartigena, Colombia, August 1983.

Radar. The radar imagery was acquired in 1972 with the Goodyear X-Band (8.0-12.0 GHz) GEMS system used in conjunction with Aero Service Corp. on Project RADAM in South America. The Canal Zone area was recorded for our use in the Latin America Remote Sensing Courses convened by the Inter Americano Geodesico Servicio (IAGS), then part of the Army Map Service (AMS), but now a part of DMA. Within this large study area, a few sites were recorded in stereo. Most of them were recorded in the near near field and the far far field, which resulted in too much parallax for stereo viewing. Some were recorded in the far near field and the near far field, and these stereo radar pairs were excellent for evaluating three-dimensional landform and major drainageways. With reference to Barro Colorado, however, there was not any stereo coverage.

PROCEDURES

The levels of technical capability used in this study were essentially equivalent to skill levels 1 and 3 as defined in table 1. Level 1 represents the job entry level, or the minimum level of training and experience needed for photo analysis. Level 3 represents the other extreme. This combination provided a means for testing and defining the observational, descriptive, and inferential skill levels required for specific photo analysis tasks, and the overall results from this and other studies formed the basis for ranking these requirements in the basic P.I. Logic report.[4] Boundaries and pattern elements were traced out on stable-base material fastened to the imagery being studied. The pattern elements that were evaluated were landform, drainage, and lineations, which are the more important ones with respect to making predictions about rock and soil identities, slopes, location of engineering materials, and surficial characteristics associated with cross-country movement. Vegetation patterns can also provide information about soil conditions, *cross-country movement*, cover and concealment, etc., but in this study, these patterns were not evaluated beyond the level of general observations. The color infrared photography that was used was of excellent quality and shows a richness of vegetation detail that could serve as a basis for a research study.

Landform. Landform refers to the shape of the land, and with respect to terrain information, it is the most important pattern element because it is so closely related to the physical properties of the materials. For example, an angular, rugged shape would be indicative of a hard resistant material; and a pattern of gently rounded shapes would be indicative of a soft, cohesive material. Wherever any of the shape characteristics change, there is a basis for a boundary and the assumption that materials and/or conditions have changed. This refers to changes in both profile and in plan. For example, if one has mapped out three landform units, then one can assume that there are at least three different materials, conditions, or combinations of the two. Because of the closed tree canopy, the land surface could not be viewed directly and inferences were made from variations in the configuration of the canopy surface. The inferred landform characteristics were examined, evaluated, discussed, and the boundaries marked while viewing the stereo air photos simultaneously by means of two Old Delft Scanning Stereoscopes, back to back. Some weeks later, new overlays were made and compared to the first set. Further observation and discussion led to a final overlay.

[4] Rinker, J.N., and Corl, P.A., 1984. *Air Photo Analysis, Photo Interpretation Logic, and Feature Extraction*. U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL-0329, AD-A153 926.

Drainage. Drainage refers to the pattern carved into the landscape by running water, including active streams as well as those channels in which water would run if water fell on the surface. As a pattern it provides information about material types, permeability, ease of erosion, relative hardness, and presence or lack of control. The layout, or plan, is related to soil texture, permeability, and ease of erosion, as well as to rock type, structure, and fractures. In general, the finer or more closely spaced the drainage net is within a soil mantle, the finer the soil texture and the less permeable the material. The patterns of elevation (gully cross section and gradient) are related to three broad soil groups (granular, silty, and cohesive) and their combinations. In the absence of a soil mantle, the patterns are related to the rock characteristics of hardness, permeability, solubility, structure, and fractures. As with landform, the drainage pattern was mapped by evaluating the variations in the shape of the canopy. The drainage pattern was first traced out by each of us independently, using a two-power pocket stereoscope. Some weeks later, this was repeated to get some idea of consistency. The results were compared and discussed. Variances were examined by stereo viewing and resolved one way or another. The final overlays were prepared by simultaneous viewing of the stereo images.

Lineations. Lineations refer to patterns of lines, excluding cultural lines such as roads, survey lines, power lines, logging traces, etc. The lines of interest are those associated with fractures in the rocks, and these are usually referred to as "joints and faults." The term "fault" is used when perceivable differential movement has occurred between the two sides of a fracture. The stresses that cause a rock to break can come from many sources: volume changes due to cooling from a liquid to a solid state, expansion of a previously compressed mass, surface stretch caused by doming and folding, and of course, plate movements. The lineal patterns that one traces on the imagery usually represent a zone of closely spaced breaks rather than just one plane of cleavage. This is particularly true when mapping on imagery such as radar or Landsat scenes. In any case, the fractures are weak zones in the rocks and are likely responsible for the initial set of the drainage pattern and subsequent landform development.

Aside from information about causative forces, the pattern is of interest because, in many areas, it can provide information about subsurface water flow, probable ground water locations, contamination routes, mineral deposits, and zones of potential instability in conjunction with engineering applications. There is no single characteristic of a lineal, or surficial trace of a fracture. It can show as a line of increased vegetation vigor or height, as a segment of drainage, as a light line across a field because of better drainage and subsequent drying of the soil over the fracture, or as a darker trace across the field, because moisture is collecting in the soil as a result of a trough-like depression along the fracture. Many pattern bits, such as shadows, etc., can fall into alignment when viewed from a given direction, and yet not be related to rock fractures. Consequently, one can trace out different sets of lineals as the sun angle changes. The best thing to do, although not often possible, is to mark the lineal on two sets of imagery taken at different sun angles and concentrate on those that are common to the two sets. When the lineals are well defined in the imagery, are visible in both halves of a stereo image, occur in different sets of imagery, can be distinguished at different viewing angles, cannot be attributed to other causes, and are consistent with geologic reasoning, the most likely explanation is that they are associated with bedrock fractures. Fractures and fracture zones can be mapped on all imagery (photo, radar, Landsat), and at all scales. Some show better in certain seasons and become faint in other seasons. In this instance, because the closed canopy prevented seeing any traces on the ground, the majority of the clues were provided by lineal patterns in the canopy and by aligned drainage segments. Exactly why the lineals show in a photo image is not known, but it is probably a result of several

things. In places, a line of trees appears taller, but in other places it seems almost as if there is a cut in the forest, but there is not.

The lineations were mapped stereoscopically and monoscopically on the photography, and monoscopically on the radar images. When done monoscopically, the image should be viewed from different orientations because all lineals are not equally apparent from the same viewing direction. The first sets were marked independently, compared, and converted to a set by viewing the imagery together. After several weeks, this was repeated and the two sets compared and converted to a final overlay.

As an aid to ground checking, a trail overlay was prepared so that one could see the approximate relations between the trails and the pattern elements. The overlay was made from the 1978 revision of the trail map printed by the Smithsonian Institution, and distributed as a handout at the Smithsonian Tropical Research Institute, Barro Colorado Island. The overlay was brought to the scale of the aerial photography and registered approximately to the center photo of the stereotriplet. In the stereo image, the overlay could be shifted in accordance with best fit, and the trails traced out on clean overlay material. In many places throughout the image there were patterns that coincided with the shape of that segment of the trail. Figure 11 shows the trail net in relation to the photo image. Figures 24 through 27 show the trail net alone, and in conjunction with the patterns of landform, drainage, and lineals. These illustrations were intended for use in the field as ground checking aids.

RESULTS

Air Photo Analysis

Figures 2 and 3 are reduced copies of the 1949 and 1979 stereotriplets of Barro Colorado Island. Both sets of aerial photography were taken with a 6-inch focal-length lens, which is a wide-angle lens when used with a 9- by 9-inch camera format. The ground separation between successive exposures is greater than with a longer focal length lens, and consequently, there is an increase in vertical exaggeration. In this case, there is an increase of about two and one-half times. This means that, in the stereo image, things seem about two and one-half times steeper and taller than they really are, which is of great help for an analysis.

Landform. Figure 4 shows the landform information derived from the 1979 stereotriplet. Five landform units were outlined and labeled with the letters A through E. These are shown as overprints on the stereo photography in figure 4B, and in line form in figure 4A. Landform unit A is the topmost unit and the boundary is defined in most places by a fairly small, although abrupt, elevation change in the canopy configuration. As a unit, the surface seems to be relatively flat, devoid of noticeable drainage dissection, and sloping gently to the west or west-southwest. There might be a lobe of this unit extending to the south from the small arm on the south side of the area that trends to the southwest, but we were not able to agree about this. This possibility is shown in figure 4B as a dotted line that forms a lobe-like extension from unit A. The intensity of rain and the amount of runoff should be similar over the island through time, and unit A has had as much exposure to erosive forces as have the other landform units, but it is there and shows little evidence of degradation. If it were a relatively soft material, it would have long since been heavily dissected, if not removed. Thus, these observations suggest that unit A is a relatively hard material that is resistant to erosion, i.e., the hardest and most durable material on the island.

Unit B is more extensive than unit A and is below it in elevation. Although its surface seems more irregular than that of A, it would still be classified as relatively smooth. Although some drainage channels have been formed, they do not seem to be well developed. The perception that one has of the slopes associated with the drainage is that they are relatively gentle and that the channels are relatively broad, at least in comparison to the channels in the surrounding area of unit C. This is suggestive of a relatively soft material that tends to have a fine texture. The overall surface resembles a section of a large sphere, or dome, in that the slopes fall away to the shore to the south, the west, and all directions in between. The highest part of B is the northeast section of the boundary. The shape, and the fact that the material supports unit A and seemingly rests on another unit, suggests the possibility of a sedimentary sequence. An additional clue can be found in the shape of the shoreline. Although only part of the shoreline can be seen in the 1979 photography, all of it can be seen in the 1949 images (fig. 2). The arcuate, cusp-like extension, the thin ridge-like extension, and the curved contours seen along the southwest segment of the shore (see fig. 4A) are typical of relatively soft, or relatively soluble, sedimentary rocks, e.g., limestone, soft granular sediments (including sandstone, siltstone, etc.), limy sandstone, or mixes of all these. Clay shales can develop rounded contours, but they do not develop the scallop, or cusp-like, arcs. And being more or less impermeable, they would show a more intensive and well-developed erosional pattern of drainage channels, assuming that such could even be detected in the canopy structure. This does not mean that clay particles are not present. There probably are clay materials interspersed, or interleaved, as relatively thin beds or in the form of accumulations of weathered residue. The three larger extensions from the southwest shoreline are typical of a sedimentary unit that has at least some calcareous material in it. In this southwest portion, there is possibly another change in the landform characteristics of this unit. The western part of the unit has a rather uniform slope as it drops down to the water, whereas the southwestern section shows a break in gradient with the lower section having a more gentle slope. The broken curving line that crosses landform unit B in a nearly east-west direction in figure 4B indicates the location of the slope change. Note also that such a boundary tends to separate the shoreline into a more indented section and a less indented section, the latter being the west edge of the unit. Whether this area created by the dotted line is a new landform unit, an extension of C, or a modification of B or C can be determined only on the ground. It is possible that the area is properly part of B and that because of fracturing, differential erosion has caused the slope changes. For purposes of simplicity, and until that area can be ground checked, we are including it as part of unit B. In summary, these observations suggest that unit B is a relatively soft sedimentary unit, granular in nature, and containing at least some carbonaceous material.

Unit C has the most rugged topography of the landform units on the island, and the parallelism of the valleys and the ridgelines indicates the presence of joint control. The ridgelines are relatively long, show steps in some places, have some arcuate sections, and show indications of parallel finger-like branches. These branches tend to extend from the ridge axis at large angles and are frequently normal, or nearly so, to the ridgeline. Such a pattern is most often associated with sedimentary units that are relatively flat lying, i.e., they are not steeply dipping. Note that the ridgelines seem to be well defined and sharply rounded. Such patterns are characteristic of coarse, granular sedimentary rocks, i.e., rocks containing gravels, sands, etc. In general, the more defined and sharply crested the ridge, the harder the material. Thus, the pattern of C suggests that it is composed of a harder material than that which makes up B. The shoreline contour shows an arcuate pattern that is also characteristic of the granular sedimentary materials. This is particularly noticeable on the northeast trending promontory that extends out from the northeast part of the unit

(lower right quadrant of the center photo of the stereotriplet in figure 4A). There are similar patterns along the northern shore of this unit.

Unit D is lower in elevation than B, and is similar in elevation to that part of unit C that abuts it. It does not show evidence of the dissection and ruggedness that is characteristic of C. Ridgelines are not as well-defined as in C, and neither are they as sharply rounded. In fact, they are so gently rounded that, in places, it is difficult to trace them. The ridgelines have some patterns that are related more to sediments than they are to either hard, igneous intrusive or extrusive masses, or to metamorphic units — the arcuate coast sections, the relatively straight ridge segments, and some nearly right angle finger-like branching, for instance. Referring to the 1949 triplet in figure 2, one can note that although the shoreline along the eastern edge has some arcuate-like indentations, it does not have the arcuate pattern, or rounded cusps, associated with either the relatively soft, or soluble, subaqueous or submarine deposits of sediments, as discussed with reference to units B and C. Although this unit has some of the characteristics of sediments, the patterns are not typical of underwater deposits of sedimentary rocks, i.e., sandstone, limestone, or shale. The slopes do not show significant breaks in gradient; so, if beds of some sort are present they must be relatively thin, making an allowance for the problem of canopy obscuration. Relatively thin means only that vertical, or near vertical, breaks in the beds are small enough that they have not forced an adjustment in the canopy surface. What this value is we do not know. Whether this unit rests on top of C or abuts it is a debatable issue. If it is the latter case, then fault action would have been required to move it into its present position. In any case, the landform patterns of this unit, whatever they represent, seem out of place with respect to the rest of the island.

Landform unit E has three parts. As units, they have the lowest elevation; they are relatively flat, i.e., they do not contain significant hills or ridges; and the boundaries that separate them from the adjacent land are well-defined elevation changes. The rounded projections, cusp-like indentations, and scallop-like edges of the shoreline contour are indicative of granular sediments, including calcareous material, i.e., some mixture, or interleaving of sandstone, limestone, limy sandstone, etc. Possibly they are extensions or modifications of other units, in that the southernmost one is part of, or related to B, the middle one to C, and the third to D. Such a definite change in landform, however, makes one think that there may be some difference in composition.

In summarizing the significance of the landform patterns, the first observation is that as there are five landform units, there are possibly five different materials, conditions, or combinations of the two. To reason out some of these possibilities, it will be easiest to start with unit C because it has some well-defined indicator patterns. The ridgeline pattern, the valley cross sections, and the characteristics of the shoreline contour are suggestive of relatively hard, coarse, granular sedimentary rocks. We do not know what the trees hide, but there are no noticeable breaks in hillside slope that would suggest the presence of massive beds. Neither do we know how thick the bed exposure needs to be before it forces some adjustment in the canopy configuration. At least one pattern element of B, which is on top of C, suggests the presence of a calcareous fraction in addition to the granular sediments. Thus, B is made up of some sequence of relatively soft, fine-grained, sedimentary units, with some calcareous matter. Unit A rests on B, and forms the high part of the island. Furthermore, the material of A must be rather hard and resistant to erosion. If it is sedimentary in composition, then it ought to have covered all of B at one time, which means that subsequent erosion has reduced it to its present size and exposed the upper surface of B, which was previously covered by A. If A is harder and more resistant, then one would think that the forces that removed portions of A would have removed B. An alternative is to consider that A was formed in place and confined, more or less, to the boundary as we now see it. Obviously, normal

sedimentation processes cannot be confined this way, i.e., establishing an elevation edge as a boundary. There is one other pattern element to consider, and that is the shape of the boundary of unit A. A hard sedimentary rock, such as a cemented sandstone, would likely show more angularity in its outline as a result of joint control. The pattern here tends to be rounded and also shows some lobe-like characteristics. One possibility is a lava flow. If such a flow covered all of B, then we would have the same problem as before, i.e., how to remove A without developing an erosional surface on B. A lava flow, however, does not have to be extensive; it can be very local. If this is the case, then the lava had to well up through weak points, such as fracture intersections. Such is certainly possible. Such is also speculation. Based strictly on the photo patterns, the most that we can say is that unit A is a hard, durable, resistant material.

The patterns of Unit D were the most difficult to map and interpret. These patterns are not characteristic of hard, competent, igneous or metamorphic rocks, nor are they characteristic of the standard underwater formed sedimentary rocks, e.g., sandstone, shale, or limestone. The ridgeline pattern is perhaps more related to depositional material than to anything else; but that observation is suggestive only. Whatever unit D is, the patterns indicate that its composition differs from that of the other landform units, and thereby is hard to explain as being formed in place, especially with its pronounced western boundary. If D is depositional, then either the material settled on C and covered it, or the material was deposited elsewhere and subsequently moved into its present position as a result of faulting. If the material simply covered C, and its present surface elevation is not significantly higher than the adjacent exposed C, then one would think that this depository mantle was relatively thin. If thin, then the relief characteristics of C should still be visible, even though subdued. Such is not the case. One would also have to explain why and how only part of such a mantle was removed. So again, the possibility must be considered that this unit came from elsewhere. A rock can be formed of water-deposited sediments, aerially deposited sediments, solidified molten rock (extrusive or intrusive), metamorphosed representatives of these, or certain combinations of the foregoing. The patterns here are not characteristic of hard, competent, igneous or metamorphic materials; neither are they in full agreement with sedimentary units, particularly the water-deposited sediments.

Unit E has patterns that are suggestive of relatively soft, probably calcareous, sedimentary sequences.

Drainage. Coming to an agreement as to locations of drainage pattern boundaries is usually more difficult than identifying landform boundaries because changes in drainage patterns frequently take place as transitions over some distance. Figure 5 shows the 1979 stereotriplet with the drainage overprint. Figure 6A shows the drainage overlay, and figure 6B shows the boundaries of the drainage patterns. Five pattern areas were identified, although two of them, 1 and 5, are similar in that there is an absence of dissection. Thus, there is a basis for predicting the presence of four different materials, four different conditions, or some combination of the materials and conditions.

Pattern No. 1 occupies the high part of the island, and no evidence of drainageways could be detected in the canopy configuration. This does not mean that they are not present, but only that, if present, they are not sufficiently developed to influence the canopy configuration. This forest has a closed canopy and requires a good bit of rain just for maintenance. Once that rain strikes the ground, it must go somewhere. Rain falling on a surface can flow over the ground as runoff, or it can drain internally into the ground. If the rain is drained internally, then the material must be permeable; and this suggests granular substances such as silt, sand, gravel, or combinations of them. Some sandstones are permeable, and although not permeable in the strict meaning of the word,

fractured igneous and metamorphic units can drain water downward through the numerous joints. Permeable soils, and a permeable sandstone as far as that goes, are relatively soft. From the edges of any such perched unit, erosion would gradually work its way inward, gully by gully, and in ever widening gullies until little, if any, of the original mass was left. Because the unit is there and the conditions that pertain as well, it follows that whatever the material is, it has the properties of hardness and resistance to erosion. Metamorphic units can have such properties. But if it were of this high a grade of metamorphism, the patterns of surrounding contact rocks should display it as well, and they do not. As noted in the last section, the landform patterns at the contact, and beyond, are suggestive of sedimentary materials.

Drainage pattern No. 2 has radial characteristics and some parallelism. The radial pattern indicates the presence of a hill, with the high point being within pattern No. 1. It is not a true radial pattern because it does not have symmetry about a point. What directional symmetry there is tends to be about a short axis that trends a little north of east. Many of the larger channels proceed to the shore with a minimum of meandering, and many of the tributaries show some parallelism. These patterns suggest conformance to a dip-slope of a fold, or of a dome, i.e., a hill that was formed by the surface being pushed up from below. Drainage patterns formed on scarp slopes, i.e., across sedimentary beds, tend to develop trellis patterns on folds and annular patterns on domes. The parallelism of the pattern could also be explained, at least in part, if this unit was homogenous throughout its mass. Then as the incisions went ever deeper, there would not be any change in physical properties to induce a change in the drainage pattern other than a development of dendritic characteristics. Based on what can be inferred from a drainage pattern that, in turn, was inferred from patterns in the canopy, pattern No. 2 is part of a hill of some sort, asymmetrical in plan, and somehow chopped off in the northern and eastern parts.

Pattern No. 3 is more complex. The drainage net is denser, i.e., has more drainageways, shows evidence of joint control, and also shows some radial characteristics. The radial pattern shows a general sloping away from this unit's contact boundary with pattern No. 2. An increase in the density of drainageways usually goes along with a decrease in permeability and an increase in susceptibility to erosion, i.e., a softer material. In elevation, the drainage cross sections show V-shaped valleys, a characteristic of coarse-grained sedimentary materials, such as sandstone, conglomerate, etc. As mentioned in the landform discussion, many of the ridges are relatively sharply rounded, which is characteristic of slightly harder materials. The many aligned segments of drainageways indicate a good bit of joint control, which means that the rock has many fractures. Fractures are weak points, and the more numerous the fractures, the faster the rate of erosion and weathering, and the subsequent removal of the bits and pieces, even though the material is relatively hard. The drainage pattern is not uniform throughout this unit. There are more channels in the northerly part than in the south. This could indicate a gradual change in composition, such as a change in ratios of particle sizes. If there is any one place where the pattern change is most noticeable, it is in the region of the dotted line that trends north northwest in pattern No. 3 of figure 6B. Based on drainage, the patterns in plan and elevation suggest that pattern No. 3 consists of some sequence of heavily fractured granular sediments, coarser than in pattern No. 2, and possibly harder.

Drainage pattern No. 4 is neither extensive, nor well-developed. Other than evidence of joint control and response to relief, it is not very informative, once one is past the observation that the pattern is not indicative of a soft, impermeable material.

The areas associated with pattern No. 5 are relatively small, and show little or no pattern of drainage. Topographically, these units are low and the drainageways are not developed enough to cause alteration in the canopy configuration.

The drainage pattern was also traced out on the 1949 stereo photography and is shown in figure 7. A comparison can be made between the two sets in figure 8. The stereo model of each set is at right angles to the other, i.e., the 1949 photography was taken along an east-west line, and the 1979 photography along a north-south line. This causes a change in perspective between the two models, which in itself, can cause variances in the perception of patterns. One significant difference is marked by the encircled area in figure 8A. Although these are the impressions that we had when viewing the stereo images on a time-separated basis, i.e., over a year between the preparation of the two overlays, one can see the possibility of the encircled 1949 (fig. 8A) pattern in the 1979 photos when they are directly compared. Although the 1979 rendition is not an unreasonable interpretation of the canopy structure, we prefer the 1949 version for this particular site. Beyond this variance, the differences in the drainage patterns are more a matter of detail than of basic structure. The 1979 photos are at a scale of 1:20,000, whereas the 1949 photos are at an approximate scale of 1:40,000. This could account for some of the differences.

In summary, the lack of dissection in pattern No. 1, and under its conditions, suggests a hard resistant material. The details of pattern No. 2 are consistent with sedimentary rocks, and are also suggestive of a sectional remnant of a small hill, such as a fold or dome. Pattern No. 3 is indicative of a fractured mass of coarse, granular, sedimentary sequences. Results for pattern No. 4 are inconclusive.

Lineations. The fracture patterns marked on the air photos are shown in figures 9 and 10. Presumably, the majority, if not all, of these lines represent fractures in the rock and not cultural features, such as power lines, survey lines, timbering operations, etc. Figure 9 shows the more obvious lineals, i.e., those that were readily apparent to the unaided eye and readily agreed to by different people. Figure 10 shows a greater complexity of lineals, and these were traced out by a combination of monoscopic and stereoscopic viewing, with magnifiers, and without, etc.

This is a large number of lineals, and very likely some percentage of them are shadow alignments within the canopy that are sun angle dependent, and bear no relation to ground conditions. The interesting part, however, is that in both figures 9 and 10, and especially in 10, the greater concentration of lineals is associated with landform unit C and its equivalent drainage area, pattern No. 3, a pattern that is more complex than the other drainage patterns. It was stated earlier that the patterns in each of these units showed evidence of joint control, and the photo-derived fracture patterns support these comments. The section of landform unit C that separates B from D has not only several intersecting sets of fractures, but the greatest density of fractures. Although there is no direct evidence of displacement, i.e., faulting, one would predict that the probability is high that such did occur in this area.

Summary of the Air Photo Analysis

Materials. With reference to materials and conditions, the landform, drainage, and fracture patterns suggest that the topmost unit (landform unit A) is a cap of hard, resistant material. Further speculation suggests the possibility of a lava flow as a source of this formation. Beneath this cap is landform unit B, which, in a geometrical sense, resembles a section of an elongated dome. This

unit is composed of relatively soft, fine-grained sedimentary sequences, such as sandstone and siltstone, and probably contains calcareous material either as interspersed beds of limestone, or as limy sediments. It ends abruptly to the north and to the east with significant changes in slope and elevation. These changes were probably caused by intensive fracturing, faulting, and subsequent removal by erosion of parts of unit B and the exposure of the underlying beds of unit C. The patterns of unit C suggest that it is composed of relatively hard, coarse-textured sedimentary sequences that have undergone intensive fracturing. The remaining largest single unit is D, which abuts C on its west, and is about on a topographic par with it. This unit has been a problem throughout the study, and even at this point, we do not know what to do with it. The most that can be said is that it seems different from the rest of the island; and if truly different, it must have been moved in from elsewhere as a result of faulting. If there is any indicative value to the photo patterns, and it is minimal, they tend towards sediment deposits, at least in part. The remaining two areas, both belonging to landform unit E, have the lowest elevations and are probably made of granular sediments, including calcareous material. Extensive jointing patterns are evident throughout, with the heaviest concentration being in unit C.

Structure. With reference to the structure that brought about the existing relations, one enters the realm of conjecture, insofar as interpreting the air photo patterns that can be seen. There is more than one way to explain the development of these patterns, but the clues needed to resolve these issues cannot be seen in the photos because of canopy obscuration.

One possibility is that of a sedimentary sequence being uplifted locally into a small dome by the intrusion of molten rock from below, with associated and subsequent jointing and faulting and with an associated, or later, extrusion of lava to form a cap (landform unit A). Intense fracturing and erosion may account for the loss of the northern and eastern portions of the upper shell of the dome, i.e., landform unit B, exposing the underlying sedimentary beds of unit C. If landform unit D at the eastern end of the island abuts unit C, as *opposed to being on top* of it, and if it has a different composition than the other units, then it could not have been formed in place, and must have been carried to its present location by fault movement.

A compression fold, i.e., an anticline or a syncline, could also result in this general pattern. In support of this, note in the stereo image of figure 3 that the island, as a hill, is not symmetrical. It is oblate, with the long axis trending a little north of east. This was discussed also under drainage. If the hill is a fold, then this is the fold axis. In order for the photo patterns to be as they are, e.g., the slopes of A and B and the drainage trend of B, the fold, syncline or anticline, would have to be plunging in a westerly direction. In either case, the sequential relation would be as for the dome, i.e., A on top of B, on top of C, and D remaining a problem. One resolution of this problem would be fault action cutting off the eastern part of the island and moving in a block of terrain from elsewhere. Because of the asymmetry (i.e., one axis is longer than the other), the dipping to the west, and no indication of the slope leveling out and changing to an eastern dip in what remains of this structure, we think that a plunging fold is the better explanation for the island's structure. There is a structural difference between an anticline and a syncline, and the distinction is an important one when looking for potential ground water, routes of contamination, petroleum products, etc. In this instance, however, the distinction cannot be made. These issues can be resolved only on the ground.

Radar Analysis

This effort was supplemental to the air photo analysis and, although several patterns were evaluated, the emphasis was on lineals, curvilineals, and other geologic structures in conjunction with another project. Figure 12 is a reduced copy of an X-band radar image of the Panama Canal area acquired by the Goodyear and Aero Service Corporations. Patterns associated with fractures, faults, and volcanic activity are evident throughout the image. Figure 13 shows the characteristics of some of these regional patterns. These were mapped as part of a research effort on the radar geology of Panama and Central America done in collaboration with geologists from the Panama Canal Commission.[5] Figure 14 is an enlargement of the Barro Colorado portion of figure 12.

Landform. The only patterns available for determining landform characteristics are variations in tone and texture, and boundary outlines such as water/land interfaces. Although variations in highlight/shadow patterns are indicative of topographic changes (flats, hills, mountains, etc.), they cannot provide the shape information that can be obtained from stereo imagery. Referring to figure 14, one can see that the tone/texture pattern is neither uniform throughout the image nor throughout the island. There is evidence of a subdued highlight/shadow relief along the northern edge of the island and in a WNW/ESE trending band between the smoother textured western and eastern parts of the island. Tracing out the interfaces between these patterns results in four landform units (1, 2, 3, 4) shown in figure 15. Area 1 corresponds roughly to the outline of air photo landform unit B, area 2 to unit C, and areas 3 and 4 to units D and E. These units resulted solely from delineating the pattern labeled as area 2. The reasons for this pattern include a greater degree of dissection (highlight and shadow) and greater relief changes, i.e., great enough to alter the shape of the canopy surface. From the standpoint of radar return characteristics, areas 1, 3, and 4 are similar. Although there are some subtle tonal variations within area 1 that might be analogous to unit A, there was nothing that we could consistently and reliably break out. In part at least, this was probably due to the fact, that, because of our work with the air photos, our minds were trying to arrange these tone variations into some semblance of landform unit A (i.e., the problem of what we really see versus what we expect to see). Anyway, based on radar tone/texture patterns, we delineated two types of landform; one type containing areas 1, 3, and 4, and a second type represented by area 2. Based on its radar highlight and shadow characteristics, unit 2 is more rugged in relief than the other units. With reference to specific pattern indicators in the radar image, the highly indented and crenulated boundary between the land and water around parts of the island and the mainland, especially the eastern coast of the western landmass, is characteristic of relatively soft and/or partially soluble sedimentary units such as limestone, calcareous sandstone, etc.

Drainage. Attempting to map this pattern in this type of region, i.e., low relief and complete tree canopy cover, is an exercise in futility, and the results are of questionable value. A few obvious segments of drainage can be noted, mostly in the lower reaches of the channels. Once beyond the obvious, reliance must be placed on highlight and shadow to find the topographic lows, and this must be done in accordance with judgments made from other factors. We are looking mostly at canopy topography and assuming that there is a relation between the canopy relief and the ground relief. Based on highlight and shadow, the lows, as well as the highs, will be located at the boundaries between these two tones. So, the problem is to sort out which boundary goes with which feature. In the radar image, the western edges of the island and other land units are brighter

[5] Stewart, R.H., Stewart, J.L., and Rinker, J.N., 1983. *Use of SLAR, SIR-A, and Landsat Imagery in Interpretation of Geologic Structures and Relations in Panama.* Presented at the Caribbean Geological Congress, Cartigena, Colombia, August 1983.

than the eastern edges. This indicates that the radar plane was to the west of the scene and the radar was "looking" towards the east. Under these conditions, the darker tone just east of a bright tone represents the backside of a hill facing away from the radar, and the boundary between these two tones will be a ridge. The next light tone east of the dark tone will be a slope facing the radar, and the boundary between it and the preceding darker tone represents a low. Sounds simple, but it is not easy to do. One finds that it is difficult to decide which direction a channel is taking, or which collector it is joining. Sometimes, what seems to be a well-defined channel cannot be connected up with anything. The result is that if the drainage is mapped several times, the maps will be different and none of them will show much detail. One such attempt is shown in figure 16. From the standpoint of general terrain information, a visual impression of an area will probably be of more use. Referring to figure 15, the tone/texture pattern (subdued highlight and shadow) of landform area 2 suggests that that area is more dissected and contains more and deeper drainage channels than the other areas, and thereby will be more rugged.

Lineations. Figure 17 shows the lineals that were mapped, and figure 18 shows lineals that are common to the radar image and the air photos. Because of the lack of locational accuracy in comparing overlays from uncontrolled stereo photos at one scale to a radar image at another scale, and with its own system distortions, one should refer to location in only general terms. Thus, figure 18 shows where photo lineals and radar lineals are in the same general vicinity. In most cases, a lineal marks a zone of fractures, not just a single cleavage, and so the term "general vicinity" is adequate. The fact that fractures show on a radar image of tree-covered ground indicates that a sizable swath of ground must have been disturbed. Going back to figure 17 one can note that, for the most part, the "common lineals" are fracture zones that carry over into land units on the other side of the lake. Also, the lineal pattern is more intensive in the area associated with air photo landform unit C, especially in the southwest/northeast trending corridor between units B and D (see fig. 4).

Vegetation Penetration. There is little transmittance of radar frequencies through vegetal material. Exactly how much, however, is not known. Obviously, some fraction of the incoming electromagnetic energy can reach the ground through holes in the canopy, whether the canopy be grass, shrubs, or trees. Of this fraction, some lesser fraction will be reflected from the ground and back into space through some combination of holes; and of this, an even smaller fraction will be going in the direction of the antenna. A vegetation canopy is a volume scatterer in that some energy from some portion of the incoming wave front can be reflected back from the first leaf or branch encountered, which can be at the top in one case, at the bottom in another, and elsewhere for others; or follow a tortuous sequence of reflections from leaf to leaf down, and leaf to leaf back up. Consequently, for such a closed tree canopy, the amount of useful reflected ground return is very limited, especially for point source targets and small irregular features. Whether or not an extended feature, such as a fracture zone with rock rubble accumulated along its length, can provide sufficient additional return to be noticed amongst the canopy volume scatterings is a moot point. Obviously, there is some low level of vegetation density that does not seriously interfere with the recording of ground detail that is within the resolution capabilities of the radar, and some high level of vegetation density that masks all of the ground detail. The amount of vegetation required to eliminate reflections from the ground depends also on the radio frequencies being used. For L-band radar (wavelengths around 23 cm) only a tall, dense, leafy woods has the necessary roughness and volume-scattering properties to eliminate specular reflections from the ground surface. For shorter wavelengths, such a canopy would be even rougher. For X-band and C-band systems, shrubs will have the same effect. For wavelengths less than 1 cm, even short grass is a rough-surfaced, volume scatterer. Aside from aspect angle, variations within the canopy are the principal

means of altering the radar return from the canopy; and, such can be caused by changes in the dielectric constant, in canopy structure, or in both. The issue is by no means resolved, but for a given frequency band, the causative agent is more likely to be variation in canopy structure, i.e., in the size, spacing, orientation, and distribution of trunks, branches, and leaves. With reference to X-band frequencies and foliage penetration, some information can be gleaned from this study. Note that, aside from the highlight/shadow pattern just discussed, the tone/texture pattern of Barro Colorado is similar throughout the island, and is also similar to an area on the mainland south of the island. This is outlined as area E in figure 19. Outside this boundary there is a pattern of highlight and shadow that can be associated with relief. We know that Barro Colorado has a dense closed tree canopy. If this same radar tone/texture pattern is found elsewhere, then one must assume that such areas are also covered with a closed tree canopy, and that the subdued highlight/shadow, or almost smooth pattern results from a lack of penetration of the radar pulse through the canopy to the ground. If this is true, then those land areas surrounding E and Barro Colorado Island that show the sharply defined highlight/shadow patterns cannot have the same kind of vegetation cover.

Frame 000119 of the 1979 color photography is adjacent to the frames that made up the stereotriplet used in the analysis, i.e., frames 000120, 000121, and 000122. Frame 000119 contains a large portion of area E, plus the southern edge of Barro Colorado Island. Both of these show as a closed canopy forest. The northwest corner of this frame shows a small portion of the land adjacent to and west of area E, and it has field patterns and slash-and-burn patterns. Air photos from 1973 show the land around area E as mostly cleared and containing field patterns. These are shown in figure 20. Figure 21 shows a portion of a 1979 Landsat MSS color composite scene of this area. It has a continuous red tone, which indicates that the ground is covered with some kind of vegetation, at least within the resolution limits of the instantaneous field of view, which is about 70x70 meters. There are, however, variations in the intensity of the red tones. There is an area of uniform darker tone for Barro Colorado, and a similar tone that corresponds in shape to area E and is so marked. The lighter tone surrounding area E represents the land that has been at least partially cleared and converted into farm land. Thus, there is a basis for a digital classification of at least part of this scene into these two classes. Although the ground around area E is covered with vegetation, it is mostly brush, grasses, crops, a few trees, etc., and greatly reduced in overall biomass. Also, on an average, most of the plants are short, as compared to trees; and, being thinner, this vegetal layer more closely corresponds to the ground surface. Thus, it does not as effectively mask the terrain, and the radar can record more of the landform and topographic detail, and some of the gross drainage features. Even with a reduced vegetal cover, however, what is there is still a scatterer, and the radar does not record fine surface detail such as roughness, rubble, slope variations, small drainage channels, etc. With reference to a dense, tropical, closed tree canopy, it is obvious that little, if any, of the X-band radio energy penetrates through to the ground and is reflected back to provide surface information.

VERIFICATION

The inability to thoroughly field check the results of the photo analysis is a weak factor of the study, and the results should be viewed from that perspective — i.e., they are interesting, suggestive, applicable to some degree, but not rigorously proved. The analysis and the overlays were completed in early 1981, and checking the results has, for the most part, consisted of comparing them to published information. The field checking that was done is discussed at the end of this section.

Landform, Material Identities, Structure. The information for checking these results came from two publications.[6,7]

Figure 22 contains a copy of the Barro Colorado portion of the USGS geologic map of the Panama Canal and vicinity.[8] It has been rotated 90 degrees so as to agree with the orientation of the stereo model of the 1979 aerial photography. Although there are obvious boundary mismatches in relation to our landform map, there is general agreement between the geological units and the photo-derived landform units, as well as agreement between photo-derived identities and the identities on the published map. Table 2 shows the comparisons.

From the standpoint of structure, one can hypothesize two possibilities: (1) a slightly elongate dome, or (2) a plunging fold with an axis trending a little north of east, and the plunge in a westerly direction. Our preference tended towards a plunging fold. Woodring states that "Structurally Barro Colorado west of the Barro Colorado fault is a shallow, irregularly warped syncline trending in an east-northeastward direction and plunging westward."[9] The Barro Colorado fault to which he alludes corresponds to the highly fractured area between our landform units C and D.

Drainage. If a detailed ground survey is not possible, the next best source of information is the published maps. The original topographic maps, upon which the others seem to be based, were photogrammetric products, i.e., the contours and elevation data were derived from an analysis of controlled air photo stereo models, probably of the 1940's. Regardless of the fact that different sets of photography are involved, a photo analysis was used to check a photo analysis: a questionable procedure. We elected to use the 1978 revised edition of the Barro Colorado Island map prepared by the Smithsonian Tropical Research Institute. It includes the trail net and drainageways. Presumably it contains the few modifications and corrections that Woodring made to the base map, which is in his 1958 publication.[10] Figure 23 shows small-scale reproductions of our drainage overlays from the 1949 and 1979 photography and the 1978 Smithsonian map. Comparing the Smithsonian map to our 1949 photography overlay, which is the simpler of our two, one sees that the most noticeable difference is in the details of the contributor channels to the main collectors. Variations also occur in the location and shapes of some of the main collectors; some of them trivial and some of them significant. One noticeable variance amongst the data sets is encircled on the 1949 drainage pattern in figure 8. A closer examination shows that the Smithsonian map depicts some main collectors that we do not, and vice-versa for the 1949 overlay. One area in which this occurs is along the west shore where we do not show the collectors on the 1949 overlay that are

---

[6] Stewart, R.H., Stewart, J.L., and Woodring, W.P., 1980. *Geologic Map of the Panama Canal and Vicinity, Republic of Panama.* Map-I-1232, Miscellaneous Investigation Series, U.S.Geological Survey, Reston, Virginia.

[7] Woodring, W.P., 1958. *Geology of Barro Colorado Island and Vicinity.* Smithsonian Miscellaneous Collections, Volume 135, Number 2 (Publication 4304), Washington, D.C.

[8] Stewart, R.H., Stewart, J.L., and Woodring, W.P., 1980. *Geologic Map of the Panama Canal and Vicinity, Republic of Panama.* Map-I-1232, Miscellaneous Investigation Series, U.S.Geological Survey, Reston, Virginia.

[9] Woodring, W.P., 1958. *Geology of Barro Colorado Island and Vicinity.* Smithsonian Miscellaneous Collections, Volume 135, Number 2 (Publication 4304), Washington, D.C.

[10] Ibid.

shown on the Smithsonian map. They do show, however, on the 1979 overlay. Because of the nature of the comparison, one cannot come to any conclusion as to accuracy in relation to ground conditions. There is a consistency amongst the photo-derived drainage information that, even allowing for the mismatches, tends to make one think that the product is a reasonable representation of the general drainage characteristics on the ground, at least for the main channels, but consistency is not proof of accuracy.

Lineations. Other than the Barro Colorado fault mentioned by Woodring[11] which is shown in the USGS map in figure 22, other sources were not found that can be used for comparison.

Field Check. Field checking was limited to three 1-day visits in 1981 and 1982, done in conjunction with other work by the senior author. Although the visits were too short to accomplish extensive field work, some general impressions were gained. Ground checking included a walk along a selected route to check relief characteristics and landform boundaries, a transect across a drainage area in the south part of the island, and a visit to an area where the lineation pattern was well developed.

A walk from the laboratory complex (see fig. 25) through a part of landform unit C, across B, up onto A, across part of B, and back to C and the laboratory, showed that noticeable changes in surface topography took place at the approximate locations ot our boundaries and that the surficial characteristics within the units agreed with our descriptions. In some areas, where lineation intersections could be located with respect to the trail net, there seemed to be more boulder-size rubble on the surface than in areas that had a less dense pattern. In areas of dense lineal intersections, one should probably assume the possibility of a rough rubbly surface with fragments as large as a meter or more. As one would predict, the upper sections of drainage channels were shallow and poorly defined; whereas, on the lower steeper slopes, many channel sections were deeply incised and had side slopes that ranged from steep, though walkable, to vertical. In these sections there were drop-offs that ranged from a meter or so to several meters. Frequently, at these spots, there was no indication of such elevation changes in the canopy as seen in the stereo image. In a walk in the southeastern part of the island on the AMNH trail just northwest of Shannon Cove (see fig. 26), one of the drainageways that was thought to be minor, turned out to be the largest of the group, and the only one with flowing water. Although on one side the approach was walkable, the other side was a steep, near vertical, wall some 10-15 meters high. From any practical point of view, there was just no indication of this in the stereo image. Without other information, one should probably assume that variations in surface relief caused by dissection can be very severe on the lower slopes.

Although the plan was to conduct a thorough field check, it was not possible. In preparation for such an event, however, a series of full scale combined overlays was prepared to help in the field work, and these are shown in figures 24-27.

DISCUSSION

Although the presence of a closed tree canopy is a severe handicap, insofar as obtaining specific information about ground conditions from image analysis, there are some general impressions that can be obtained about the terrain in terms of landform, drainage and degree of

[11] Woodring, W.P., 1958. *Geology of Barro Colorado Island and Vicinity.* Smithsonian Miscellaneous Collections, Volume 135, Number 2 (Publication 4304), Washington, D.C.

dissection, identities, composition, and properties. Certainly some information can be derived to support some of the Army's terrain information needs associated with cross-country movement, cover and concealment, lines of communication, etc. Because the task is difficult, and because the levels of skill and experience required are higher than for a subhumid region or for an area that has been cut over, more time is required. There is another aspect that should be mentioned. In this study the area of interest was an isolated land unit, i.e., an island, and patterns associated with the land/water boundary were very helpful in reasoning out compositional characteristics. Without this information from the land/water boundary, the authors could not have accomplished as much as they did.

Analysis Evaluation

Landform. Compared to the geological maps, the boundaries were in reasonable agreement with respect to location of the units, extent, and general outline. Our descriptions of landform shapes were in agreement with published literature, and with the ground observations that were made in a few localities. As is well known, a closed tree canopy obscures topographic detail and smoothes out the overall surface geometry. There were some vertical drops of 10 or more meters that did not cause a noticeable change in the canopy structure. In hindsight, one could notice a slight canopy variation in the stereo image at some of the approximate locations, but it was not noted during the analysis.

Identities and Composition. With reference to the characteristics of hardness, softness, resistance to erosion, and possible or probable rock types, the predictions were at least fair. Of the five landform units and their predicted compositions, four were in general agreement with the published literature. Note that the water/land boundary was important to part of this.

Drainage. Although different patterns were mapped (patterns sufficiently well defined to provide information about physical characteristics), the relation between the photo-derived drainage net and the existing ground drainage net has not been determined.

Lineations. No way to check.

Follow-up. In order to resolve some of the issues about the effect of a closed tree canopy, especially on the drainage pattern, the authors started a search for sites that are now clear-cut, but which had previously supported a closed canopy forest. Furthermore, there must be preclearing and postclearing stereo aerial photography of the sites. Some potential sites have been identified in Panama, and if they prove usable, a second phase of this study will begin.

Required Skill Levels

One objective was to establish the levels of skill needed to identify pattern elements, trace out the pattern and its boundary, describe the characteristics, and interpret the results. Table 1 defines three levels of skiil, training, and experience with 1 indicating entry level qualifications, 2 indicating the mid-point, and 3 indicating the highest level. Table 3 shows the results of the skill evaluation as applied to specific information elements and tasks. With reference to mapping patterns and boundaries associated with landform, drainage, and lineations, the following general comments apply. In all instances, level 3, or advanced level 2, is needed to interpret the patterns.

Landform. With reference to boundary location and general three-dimensional shape of the landform, there was good agreement between skill levels 1 and 3; enough so that level 1 probably represents the minimum requirement to map this factor.

Drainage: Main Channels. The drainage pattern was the most difficult to map for both skill levels. For this part, however, there was good agreement between skill levels 1 and 3 with reference to both location and shape. The variances between sets prepared by the two analysts were no greater than the variances between two sets prepared by the same analyst at different times.

Drainage: Contributory Channels. Skill level 1 mapped about 50 percent of the channels that were mapped by skill level 3. Of this, about a third to a half was in agreement as to location and shape. Note that this refers to agreement between the two sets, not between the sets and ground truth.

Drainage: First Order. None of the first-order detail was mapped by skill level 1.

Lineations. In general there was good agreement between the sets as mapped by skill levels 1 and 3 with respect to location and extent. Skill level 1 usually mapped fewer, and each of the analysts noted lineals that the other had missed but agreed to them when they were pointed out.

A parallel study by the same authors involved a temperate region rural site that had some 60 to 70 percent of the ground surface free of tree cover. Consequently, much more of the shape variations within the ground surface could be seen. For this site it was easier to identify and map landform pattern elements and their boundaries, and there was excellent agreement between the independently prepared sets. The tropical closed tree canopy site had a complexity which made all aspects of the analysis more difficult and more time consuming.

Application to Army Information Needs

Although the terrain information needs of the Army are many and varied, only a small number of them are outside the domain of civil needs, and of these, many rely on nothing more than a different evaluation of the same basic pattern information. Extracting from some of the published terrain information needs, and excluding items not associated with humid regions, produces a list that includes: location of usable ground water; location of engineering materials (sands, gravels, aggregate, timber); natural cover and concealment potential (topography and vegetation); landform types; and ground surface characteristics associated with cross-country movement (slopes, soil and rock types, surface roughness, obstacles, vegetation type, height, spacing, etc.). All of these needs can be supported, to at least some extent, by information obtained from imagery analysis, particularly from stereo aerial photography. Furthermore, the information for most of the needs is based on inferences drawn from an evaluation of the basic patterns of landform, drainage, vegetation, tone/texture, lineations, etc. Table 3 shows a list of information needs associated with some Army application tasks, and the levels of skill and experience required to derive such information from an analysis of imagery of a closed tree canopy area.

The information elements in table 3, being but a portion of a larger group of terrain characteristics and being results of studies limited in scope, form an incomplete list. Additional research, coupling photo analysis to careful ground checking, will better define the quantitative and qualitative limits of such derived information, as well as provide additional elements. In an area

with a closed tree canopy, the only thing that the analyst sees is trees; and from the well-defined vegetation patterns in the excellent color infrared photos used in this study and from other in-house projects, it is obvious that much information could be derived about the characteristics of the trees themselves. This is in addition to the inferred terrain information. We did not, however, tackle the vegetation patterns in this study. From previous experiences within ETL, it is known that in many instances one can make good estimates of vegetation characteristics, including crown diameters and some stem spacings. This information, coupled with tone/texture patterns, canopy shapes, and crown shapes within any bounded vegetation area, should provide a basis for the specialist to predict probable vegetation characteristics within that area in terms of average canopy height, average stem spacing, average stem diameter, amount of understory, etc., and do so in a relatively short time. The same reasoning applies to ground surface characteristics in that better relations can likely be established between landform, drainage, rock type, structure, and fractures so that the analyst can predict the average slopes, roughness, rubble, obstacles, stability, etc., within a bounded landform unit.

The information elements must then be evaluated with reference to applications such as cross-country movement, cover and concealment, location of engineering materials, etc. Some of this would require other specialists, e.g., someone knowledgeable about vehicle characteristics.

CONCLUSIONS

The conclusions will be considered in relation to the objectives stated early in the report.

OBJECTIVE 1. To determine the approximate levels of ground information that can be obtained by an air photo analysis of a tropical area that has a closed canopy of trees, i.e., the ground is not visible in the photos, and one does not have the use of auxiliary information.

Conclusion

A closed tree canopy greatly reduces the quantity and quality of information that can be derived from imagery, with little to nothing being obtainable about ground surface characteristics such as roughness, obstacles, etc. Some general information can be inferred about landform, slopes, major drainage dissection, vegetation, and, under certain conditions, about rock types and geologic structure. A summary of the types and quality of information derived from this study is shown below. The quality evaluation refers to the comparison of the image-derived information to published information, field checks, and previous experience.

TYPE	QUALITY
Landform boundaries	Good
Landform shapes	Good
Material properties	Fair
Rock types	Fair
Main drainage channels	Not verified - probably good
Contributor channels	Not verified - probably fair
First order drainage	Not verified - probably poor
Lineations (joints and faults)	Not verified - probably fair
Geologic structure	Fair

OBJECTIVE 2. To determine what levels of terrain information in terms of lineations, structure, and landform can be derived from an analysis of X-band radar imagery of a closed tree canopy area.

Conclusion

Because of the intervening mass of vegetation, and the coarseness of the resolution element, only general information can be obtained about these factors. Some well-defined landform boundaries, such as those between water and land, had sufficient detail that one could predict probable rock types. Rugged, deeply incised landforms with large relief differences cannot be masked by a tree canopy, and such areas will have enough radar pattern detail to provide some geologic information. For areas of relatively gentle and moderate relief, such as Barro Colorado and its surrounds, a closed tree canopy masks most of the topographic variations, and but little information can be obtained about landform shapes, drainage, etc. Detailed surface information such as roughness, rubble, local slope changes, drainage channels, etc., cannot be obtained. Refer to table 3 for details. A summary of information type and quality follows:

TYPE	QUALITY
Regional landform boundaries	Fair to good
Local landform boundaries	Poor
Landform shapes	Limited and poor
Material properties	Limited and poor to fair
Rock types	Limited and poor to fair
Main drainage channels	Limited and poor
Other drainage	Cannot be done
Regional lineations	Not verified - probably good
Regional geologic structure	Fair to good
Local geologic structure	Limited and probably poor

OBJECTIVE 3. To determine what levels of skill and experience are required to derive the various information elements.

Conclusion

Higher levels of skill, training, and experience are required for analyses of closed tree canopy areas than for areas where much of the ground surface is exposed. With reference to the skill levels (1 indicating job entry level, 2 indicating a mid-level, and 3 indicating the highest level), a skill level 1 is the minimum that can be used for mapping landform boundaries and main drainage channels. Skill level 2 is the minimum for mapping the other pattern elements. Interpreting the patterns requires level 3, or advanced level 2. Refer to table 3 for details.

OBJECTIVE 4. To evaluate the results from objectives 1, 2, and 3 in relation to some stated Army information needs.

Conclusion

To the question of how much air photo-derived information can be obtained over a closed tree canopy area, the answer is "Not a lot, but at least something." And, the restrictive clause is that it will be difficult, time consuming, and require high skill levels. Although the analysis of stereo aerial photography is a practical and reliable way of meeting military information needs with respect to terrain characteristics, a closed tree canopy greatly reduces the quantity and quality of information that can be derived from the imagery. Nevertheless, some general information can be inferred about landform, slopes, major drainage dissection; a lesser amount about rock and soil types and geologic structure; and practically nothing about surface characteristics such as roughness, fine drainage dissection, obstacles, etc. With reference to radar imagery, the amount of information to be gleaned would be even less. A significant aid to this study was the fact that the area of interest was an island, and the land/water interface provided pattern clues about composition. If this had been a component of a larger area we would not have done as well. Furthermore, it would have required an analysis of regional type imagery to set the stage for the local study.

Table 1. General training and experience associated with three levels of skill that represent the extremes and the midpoint.

1	Minimum level of training - High school diploma, four weeks of specialized training, plus four weeks of on-the-job training for each specialty, and twelve weeks of experience.
2	In addition to the above, this level requires one or two years of experience, and considerable knowledge (college level) about at least one specialty, such as bridges and road classifications, land cover classification, some land use classification, general soils mapping, landform, drainage, vegetation, geology, etc.
3	This level requires an unusual depth of knowledge (graduate level) about a specialty, as well as a working knowledge of several disciplines, plus considerable working experience.

Source:
Rinker, J.N., Ehlen, J., Krusinger, A.E., Currin, T.R., Poulin, A.O., McCracken, P.B. 1976. *Capabilities of Remote Sensors to Determine Environmental Information for Combat.* ETL Report 0081, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, 22060-5546, November 1976, AD-A035 139.

Table 2. A comparison of photo-derived identities and the published identities.

PHOTO LAND-FORM UNIT	MATERIAL IDENTITIES		
	PHOTO DERIVED	USGS[1]	WOODRING[2]
A	Hard, resistant rock.	Tb Basalt.	Tb Basalt.
B	Sedimentary sequences, relatively soft, fine grained, calcareous.	Tcm Caimito Formation. Tuffaceous sandstone, tuffaceous siltstone, tuff, and foraminiferal limestone.	Tcm Caimito Formation. Consists chiefly of tuffaceous sandstone and siltstone. Some hard and soft foraminiferal limestones, and other constituents. Softer than the Bohio Formation.
C	Sedimentary sequences, relatively hard, coarse textures.	Tbo Bohio Formation. Conglomerate, principally basaltic and graywacke sandstone.	Tbo Bohio Formation. Nonmarine and marine strata. Principally conglomerate of boulders, cobbles, and pebbles of basalt, fossiliferous sandstones, carbonaceous shale.
D	Uncertain.	Tcv Caimito Formation. Volcanic facies, agglomerate, tuffaceous graywacke.	Tcv Caimito Formation. Volcanic facies.
E	Sedimentary sequences, soft sandstones, calcareous.	No such unit. Are parts of Tcv and Tcm.	No such units.
	Note: USGS symbols and definitions are from USGS map (see source 1)		
STRUCTURE			
Island	Plunging Fold. Elongate Dome.	------------------	Plunging syncline.

Sources:

[1] Stewart, R.H., Stewart, J.L., and Woodring, W.P., 1980. *Geologic Map of the Panama Canal and Vicinity, Republic of Panama.* Map-I-1232, Miscellaneous Investigation Series, U.S.Geological Survey, Reston, Virginia.

[2] Woodring, W.P., 1958. *Geology of Barro Colorado Island and Vicinity.* Smithsonian Miscellaneous Collections, Volume 135, Number 2 (Publication 4304), Washington, D.C.

Table 3. Skill levels required for deriving information by analysis of stereo aerial photography and radar imagery of a tropical area with a closed tree canopy.

Information Elements		Photo 1:20,000			Radar X-Band		
These are primarily associated with: Cross-Country Movement, Cover and Concealment, Location of Engineering Materials		Obtainable	Skill Level	Method	Obtainable	Skill Level	Method
Landform	Boundaries	+	1	d	L	1	d
	Profiles (slopes)	+	2	i	0	-	-
	Description/Interpretation	+	2	d,i	L	2	d,i
Drainage	Main Channels	+	1	i	L	1	i
	Contributors	L	2	i	0	-	-
	First Order	0	-	-	0	-	-
	Degree of Dissection	L	2	i	L	2	i
	Cross Section	0	-	-	0	-	-
	Stream Width	0	-	-	0	-	-
	Stream Depth	0	-	-	0	-	-
	Bank Height	0	-	-	0	-	-
Geologic Structure		+	2	d,i	L	2	d,i
Rock Type (Igneous, Metamorphic, Sedimentary)		+	2	i	L	2	i
Soil Type		L	2	i	0	-	-
Lineations		+	1	d	+	1	d
Surface Characteristics							
	Roughness	0	-	-	0	-	-
	Rubble	L	2	i	0	-	-
	Obstacles	0	-	-	0	-	-
The evaluation with respect to vegetation is based on general observations from this study, plus results from other in-house tropical studies.							
Vegetation	Type	+	2	d	0	-	-
	Species	L	2	d	0	-	-
	Crown Diameter	L	2	d	0	-	-
	Stem Spacing	L	2	i	0	-	-
	DBH	L	2	i	0	-	-
	Canopy Height	L	2	i	0	-	-

Note: The column headed "Obtainable" indicates whether a given element can be obtained from the given imagery. A "+" symbol means that the cited imagery is a practical way to derive the requested information (not 100% of it, but at least a significant portion of it). The symbol "L" means that there are limitations as to how much of the information can be obtained. The symbol "0" indicates that, for all practical purposes, the requested information cannot be obtained from an analysis of the cited imagery. The numbers in the skill level column are defined in Table 1 with 1 meaning an entry level of skill and 2 being more advanced. They indicate the minimum levels of skill and experience needed to derive the requested information. The column headed "Method" indicates how the information is obtained. The symbol "d" means direct observation of the element in the imagery. The symbol "i" means that the information cannot be seen directly, but must be inferred.

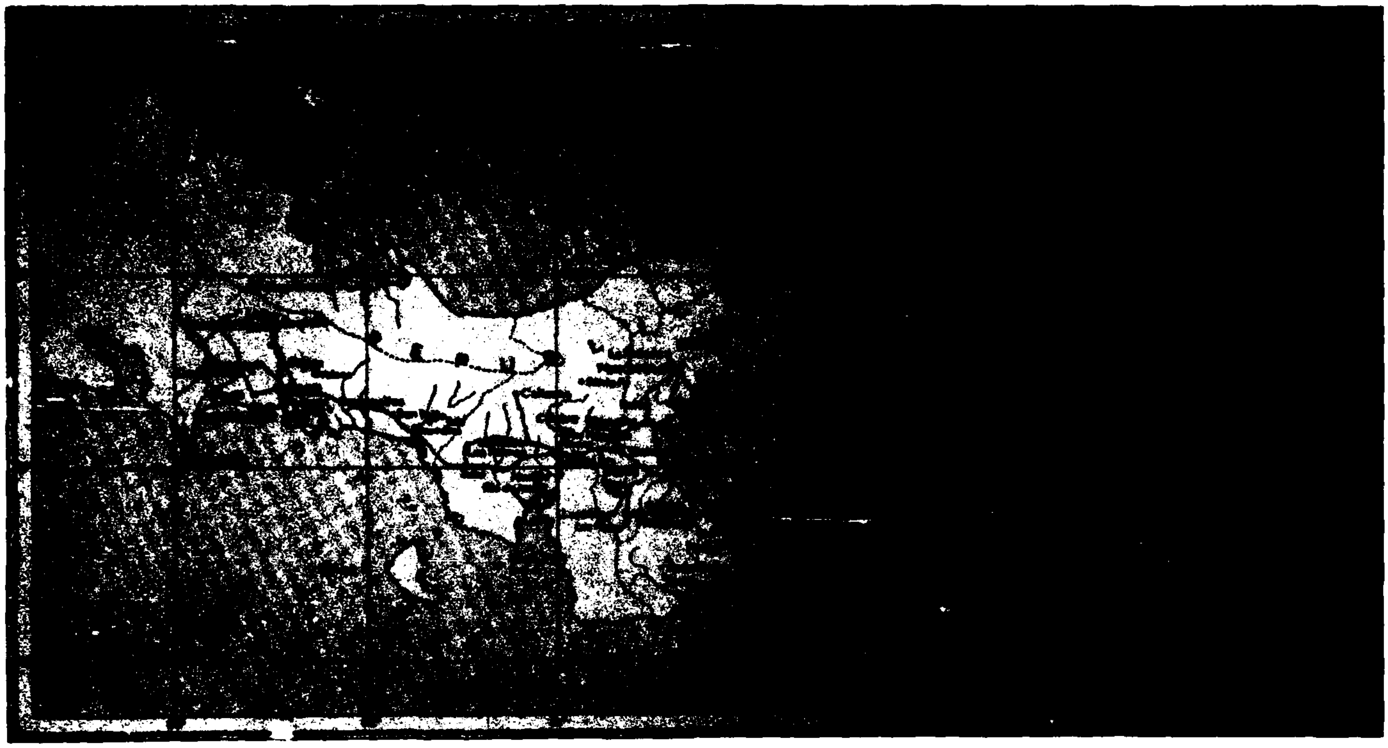


Figure 1. Location Maps for Barro Colorado Island, Panama. These were copied from the map, *Canal Zone and Vicinity*, Series E661 Edition 6-DMATC 1974, 1:100,000. The upper map is a 1:1 copy of an insert on the map. The lower map was reduced in scale to about 1:200,000.

Figure 2. Stereotriplet of Barro Colorado Island. U.S. Army photography 4RS-7/MISS TM-27, 1 January 1949, Frames 36, 37, and 38. Original scale 1:40,000. Scale of this illustration is about 1:49,000.

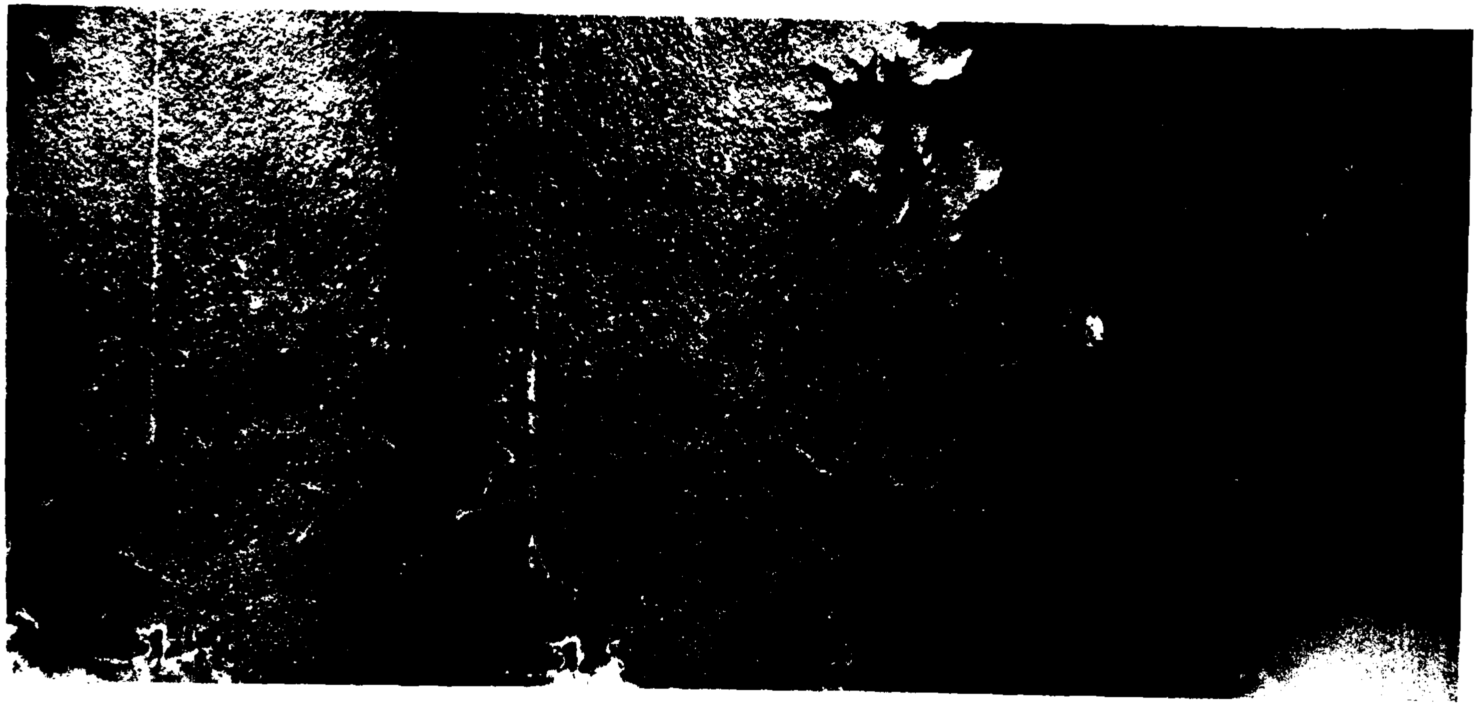
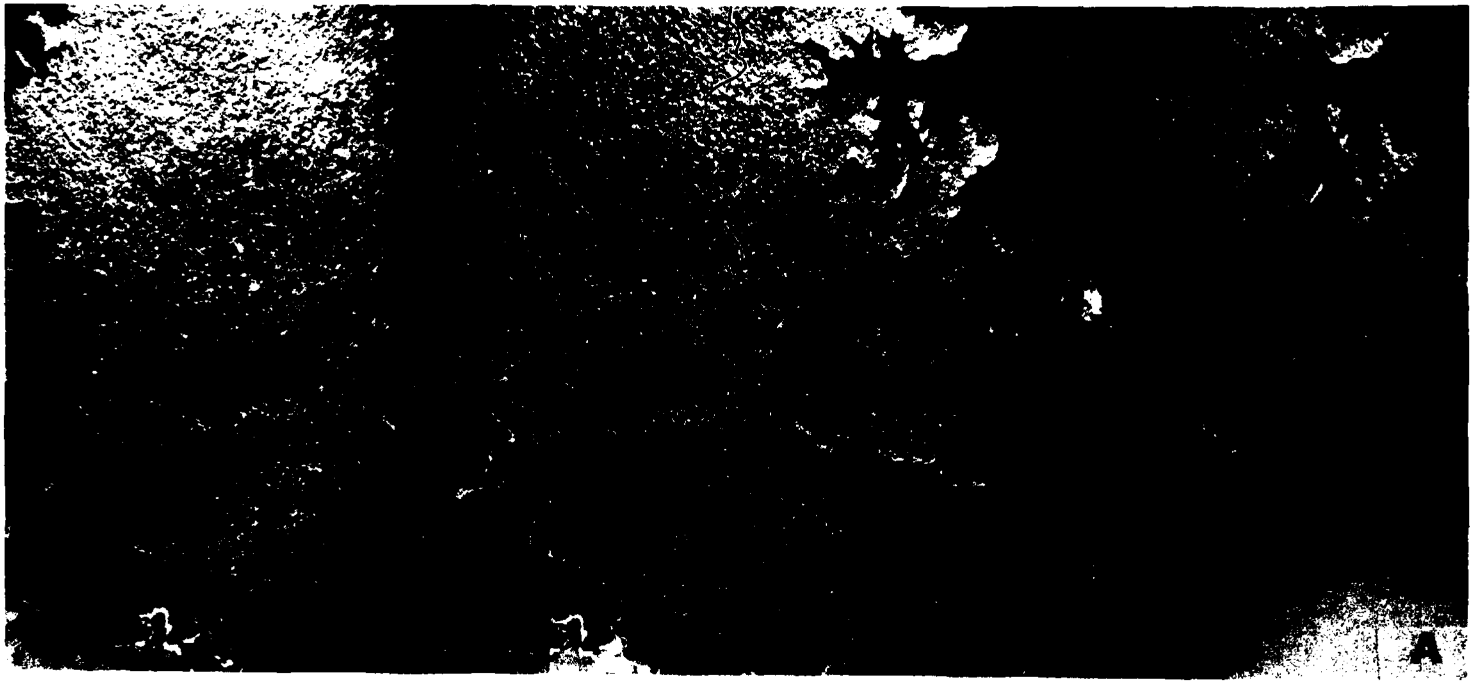


Figure 3. Stereotriplet of Barro Colorado Island. Black and white copy of Ektachrome infrared photos, taken by IGNTN, Panama, and designated PC-AID Panama R-4, March, 1979. Original Scale 1:20,000. Scale of this illustration is about 1:49,000.



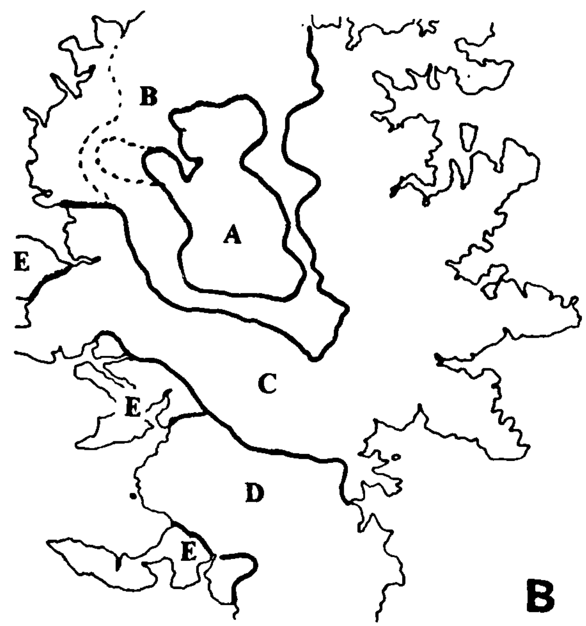


Figure 4. Stereotriplet with Landform *Overprint* (1979). The landform overlay "B" has been reduced in scale to fit on the page. The dotted lines in "B" indicate possible landform boundaries that were not distinct enough to include in the *standard marking*.

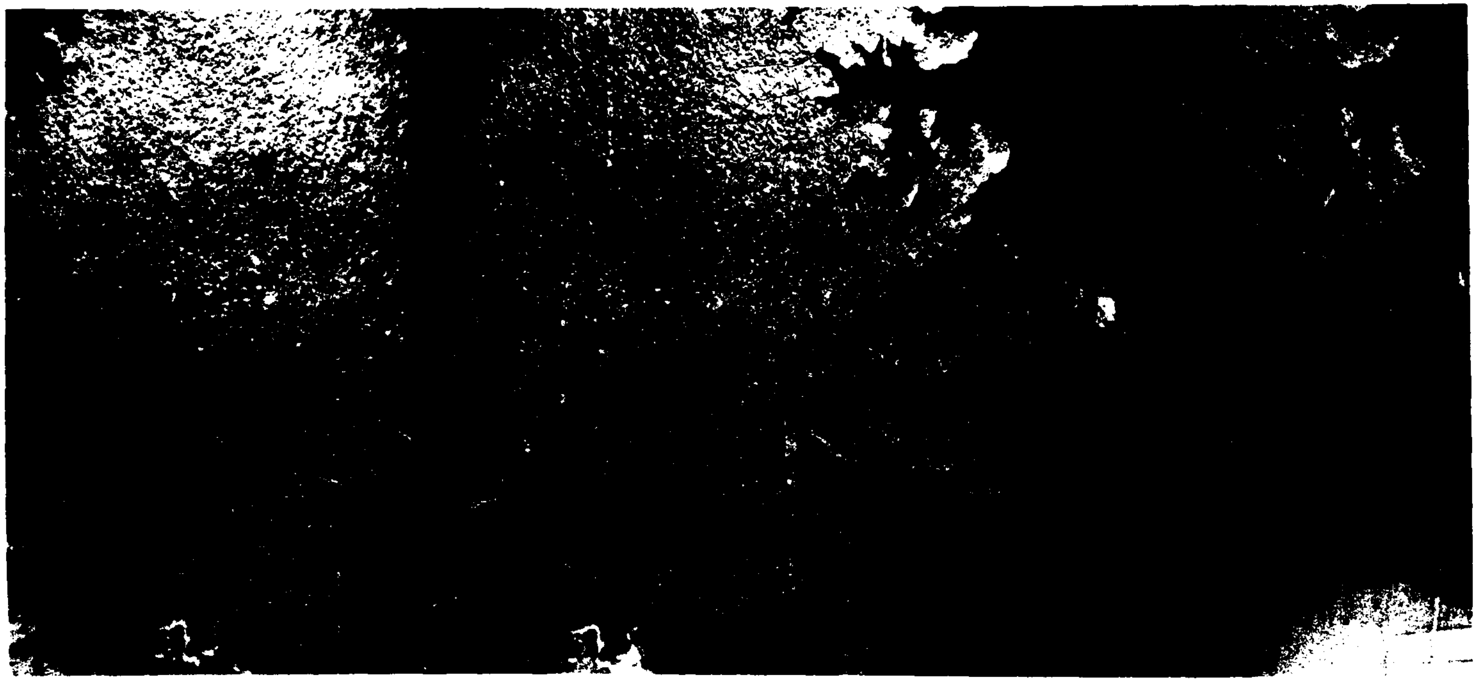


Figure 5. Stereotriplet with Drainage Overprint (1979). The drainage overlay and pattern breakout are shown in figure 6.

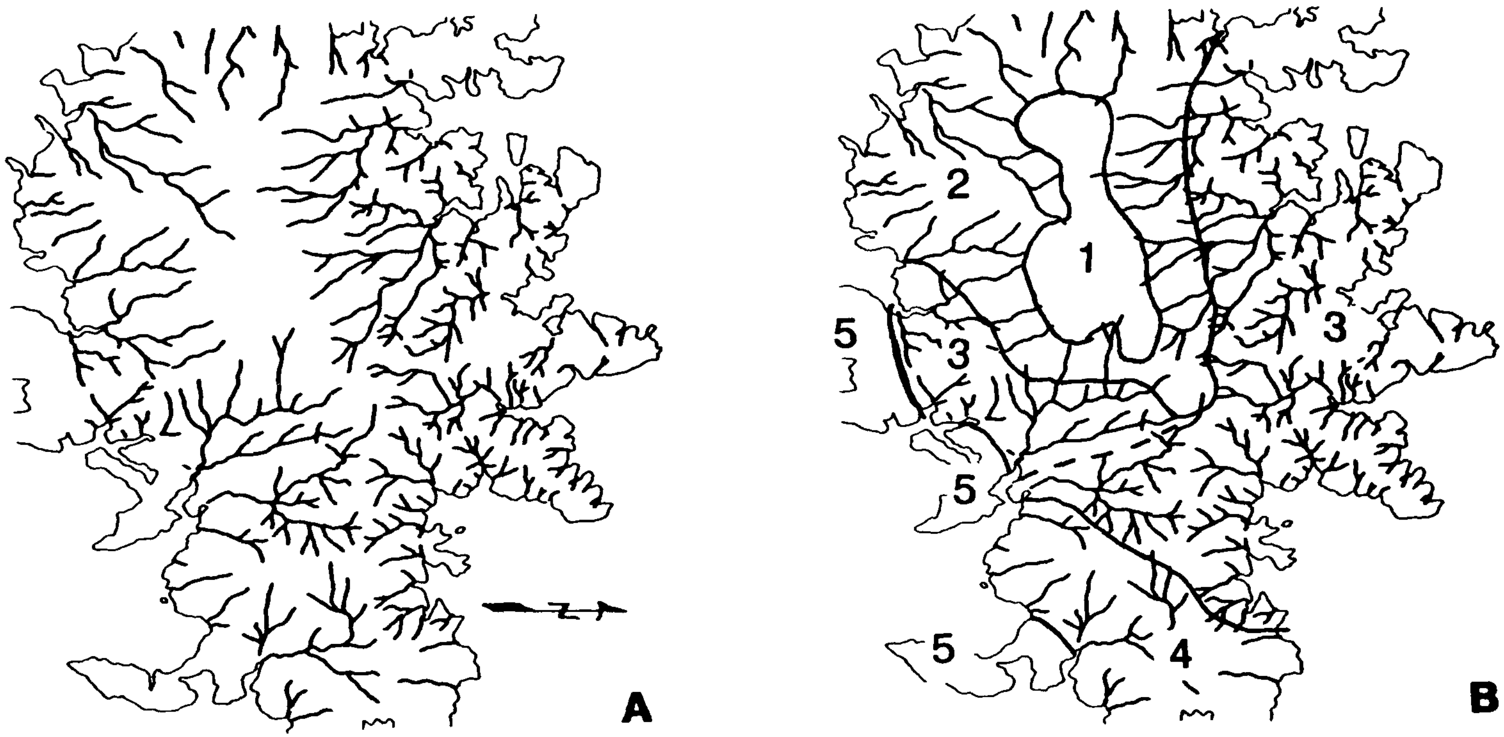
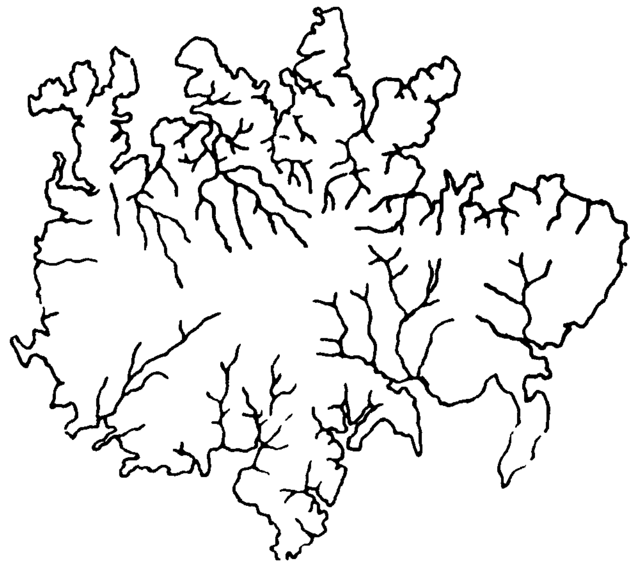


Figure 6. Drainage Overlay and Boundaries (1979). The boundaries of the different drainage patterns are shown to the right. The dotted line in pattern unit 3 marks the location of a transition zone in that pattern, in that there are more short tributaries in the northern part than in the southern part.

Figure 7. Stereotriplet with Drainage Overlay (1949). Below is the 1949 stereotriplet of Barro Colorado Island. To the right is the drainage overlay. It has been reduced in size in order to fit on the page. The 1949 stereotriplet is at right angles to the 1979 photo set.



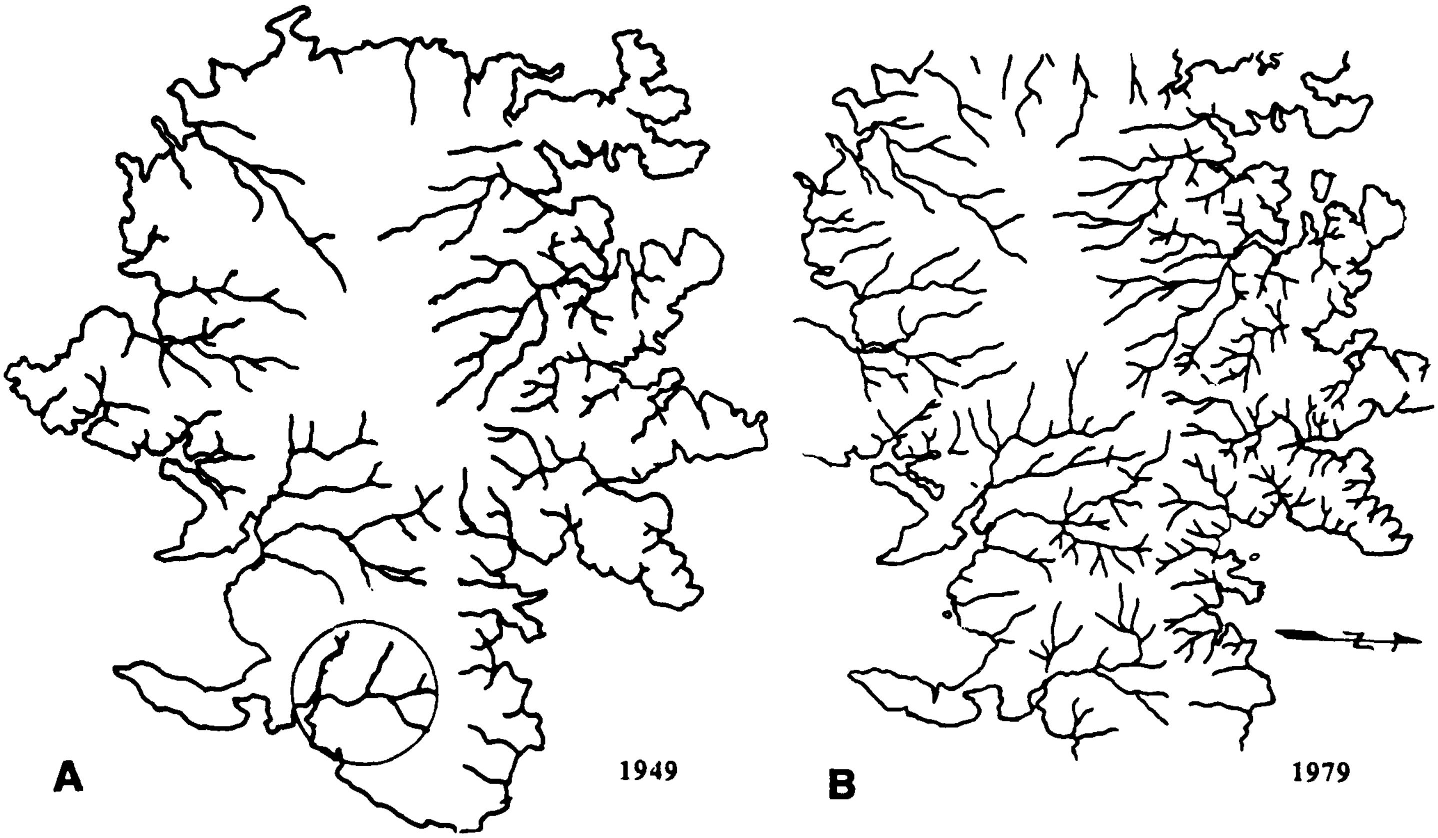


Figure 8. Comparison of Drainage Patterns (1949 and 1979). The encircled area on the 1949 drainage overlay marks the most serious mismatch between the two patterns.

Figure 9. Stereotriplet with Obvious Lineals (1979). The lineation overlay is to the right, at a reduced scale to fit on the page.

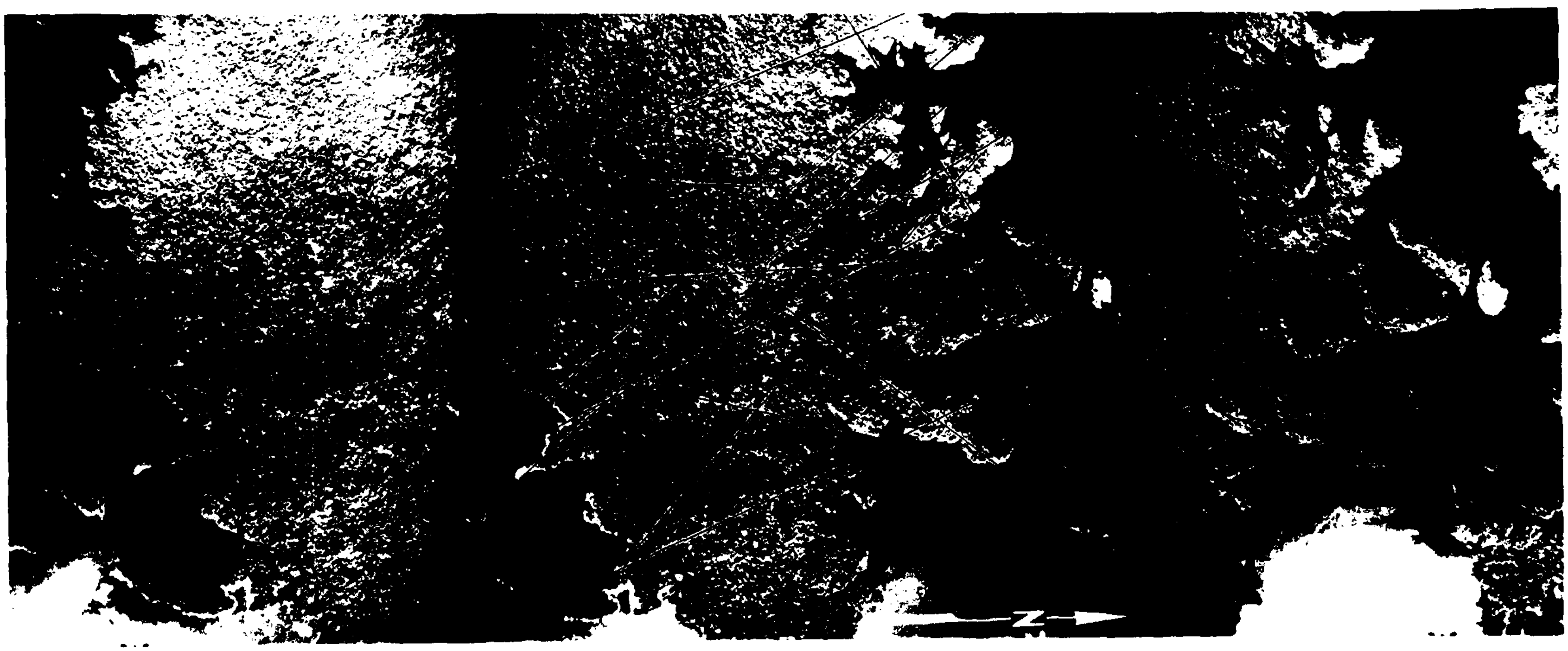
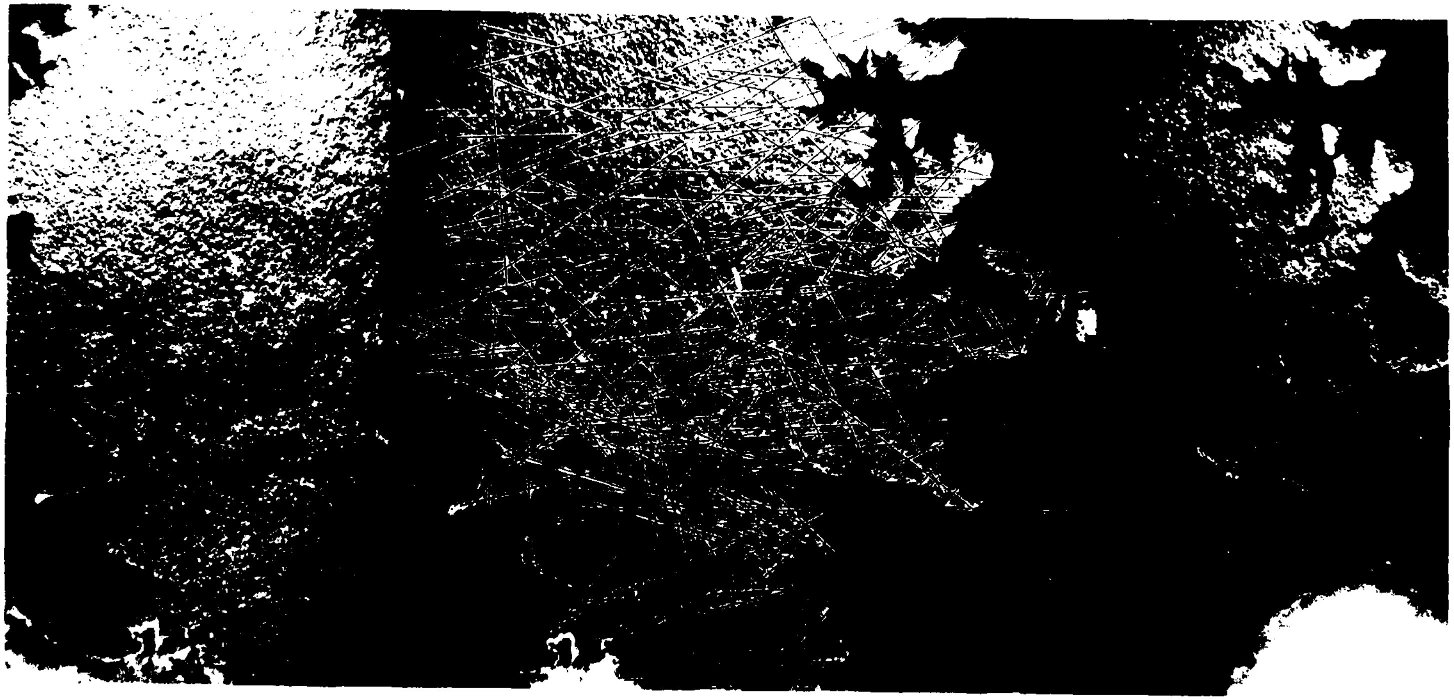


Figure 10. Stereotriplet with All Mapped Lineals (1979). The lineation overlay is to the right, at a reduced scale in order to fit on the page. *Although we mapped in* seriousness and in agreement, we consider this a case of overkill. It also illustrates one problem in mapping lineals; that of separating lineals induced by a happenstance alignment of spurious pattern elements from the real thing, i.e., fracture controlled alignments.



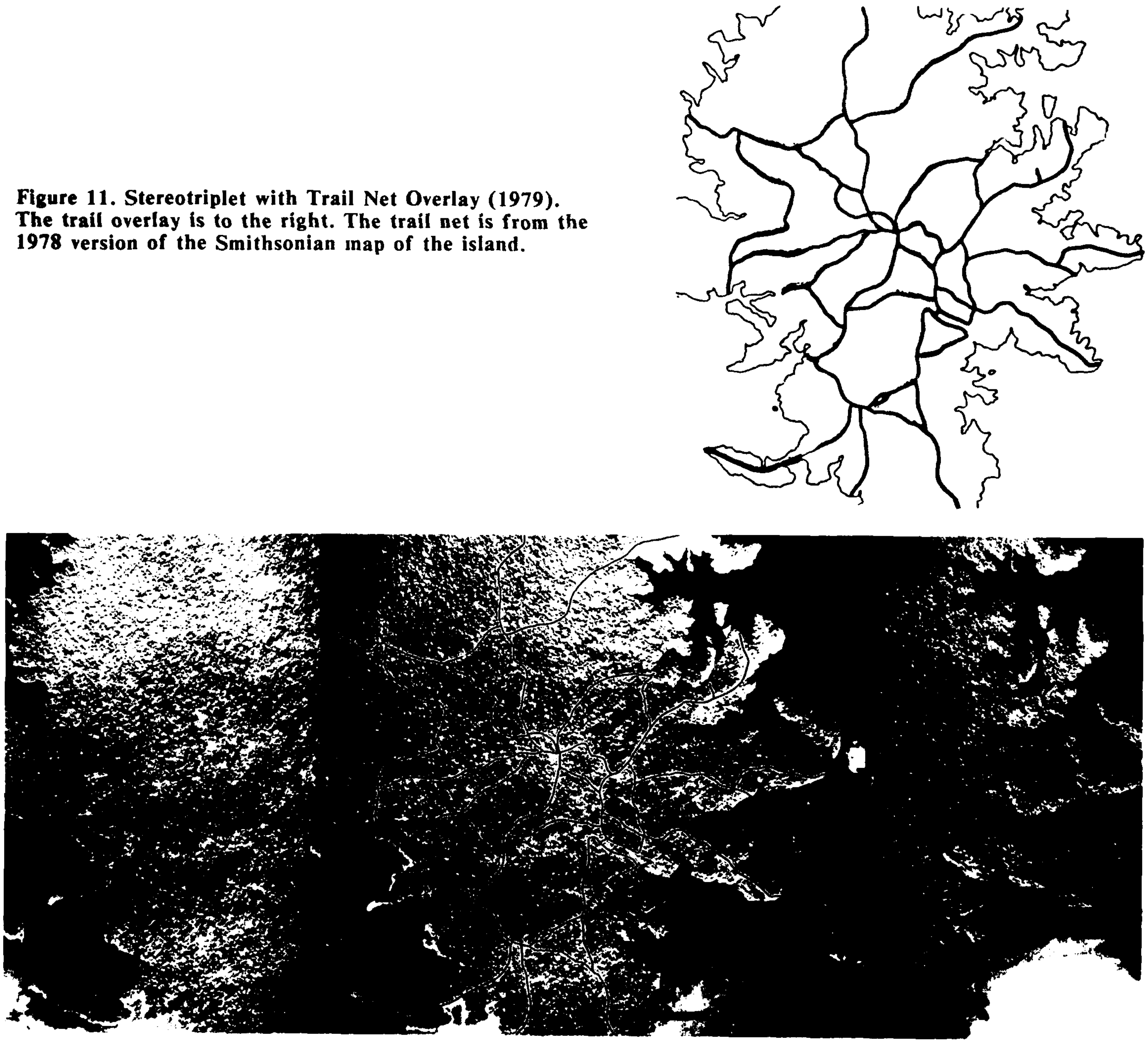


Figure 11. Stereotriplet with Trail Net Overlay (1979). The trail overlay is to the right. The trail net is from the 1978 version of the Smithsonian map of the island.

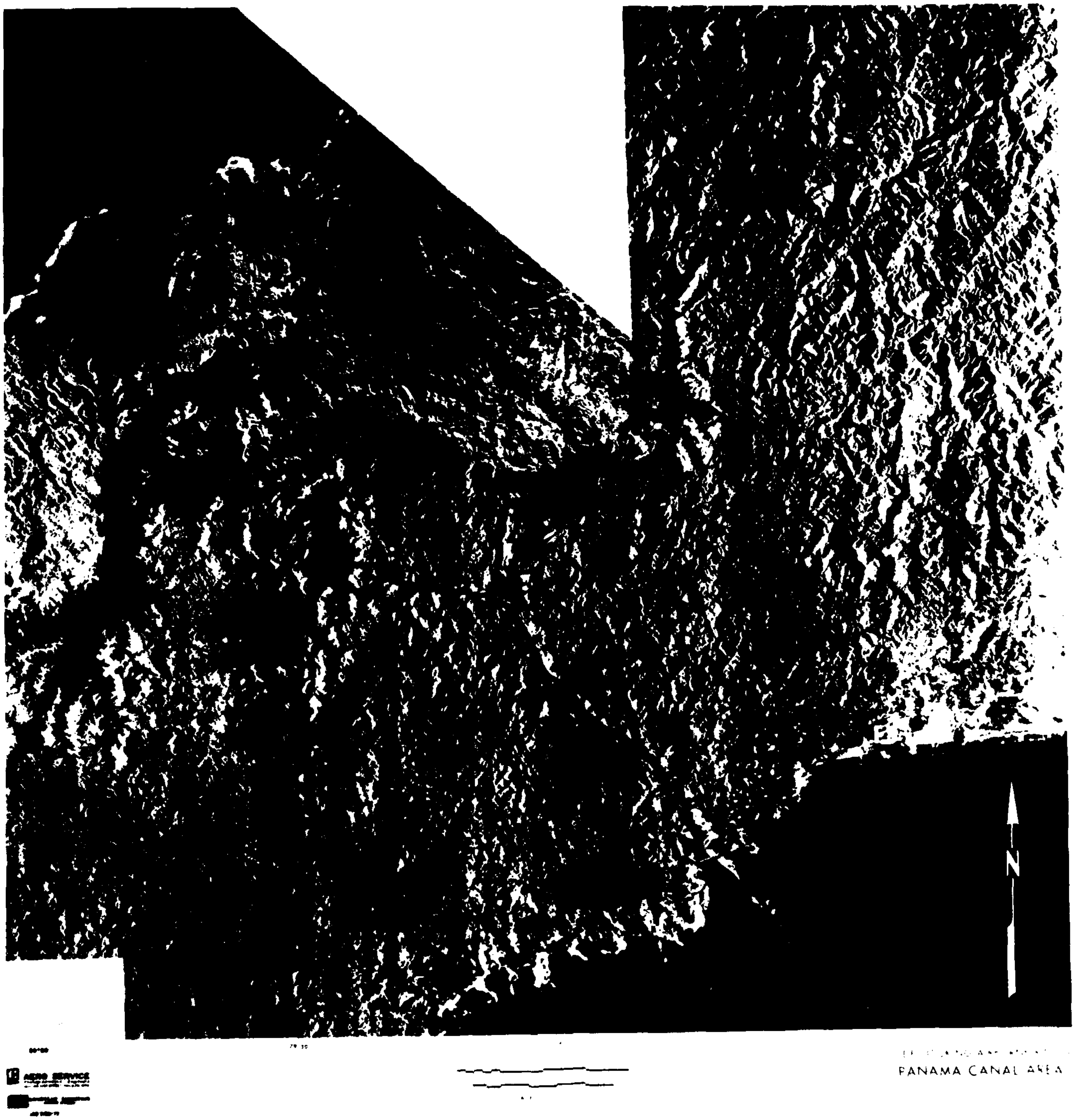


Figure 12. Goodyear X-Band Radar Image of the Panama Canal Area. The imagery was recorded in 1972 by Goodyear and Aero Service Corp. The approximate scale is 1:400,000.

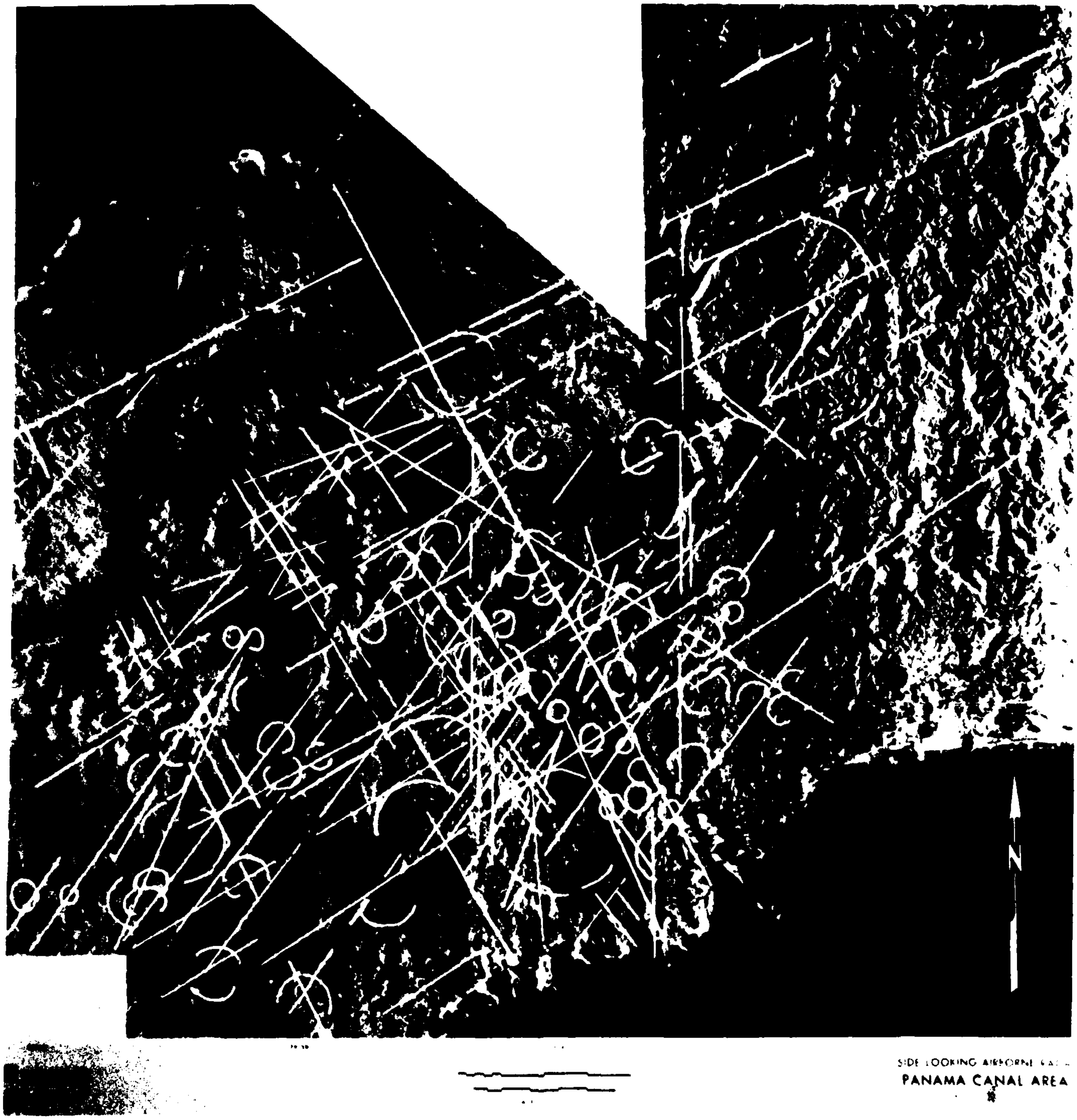


Figure 13. Radar Image with Lineals and Curvilineals Overlay. Goodyear/Aero Service radar image with an overprint of regional lineals and curvilineals. The latter are associated with volcanic activity, i.e., old calderas, doming, etc. This was part of a cooperative study with geologists of the Panama Canal Commission (see footnote 3).

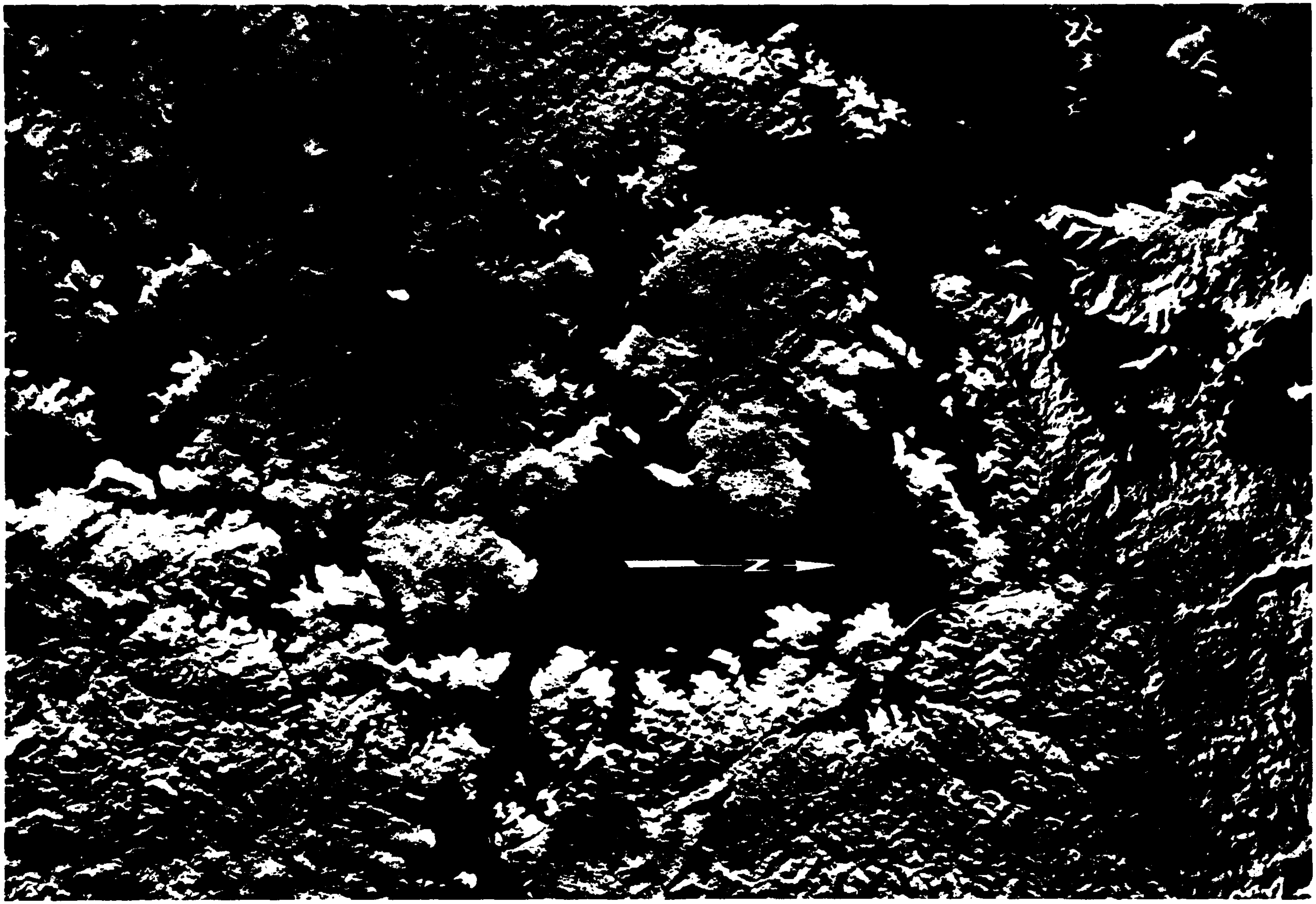


Figure 14. Enlarged Radar Image of Barro Colorado Island Area. An enlargement of the Barro Colorado area from the Goodyear/Aero Service radar image. The slightly wavy north/south line just above the central area is a mosaic line.

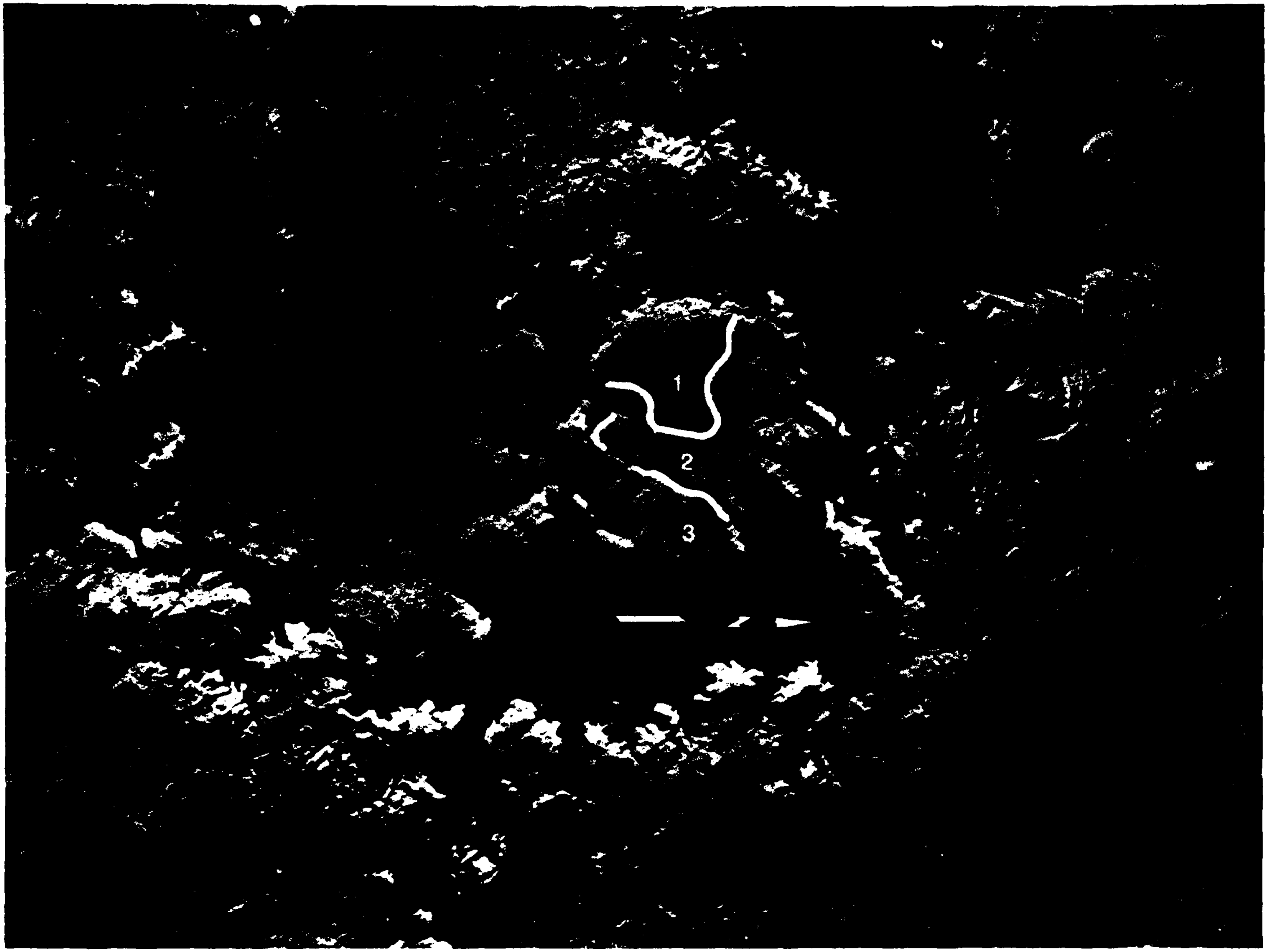


Figure 15. Radar with Landform Overlay.

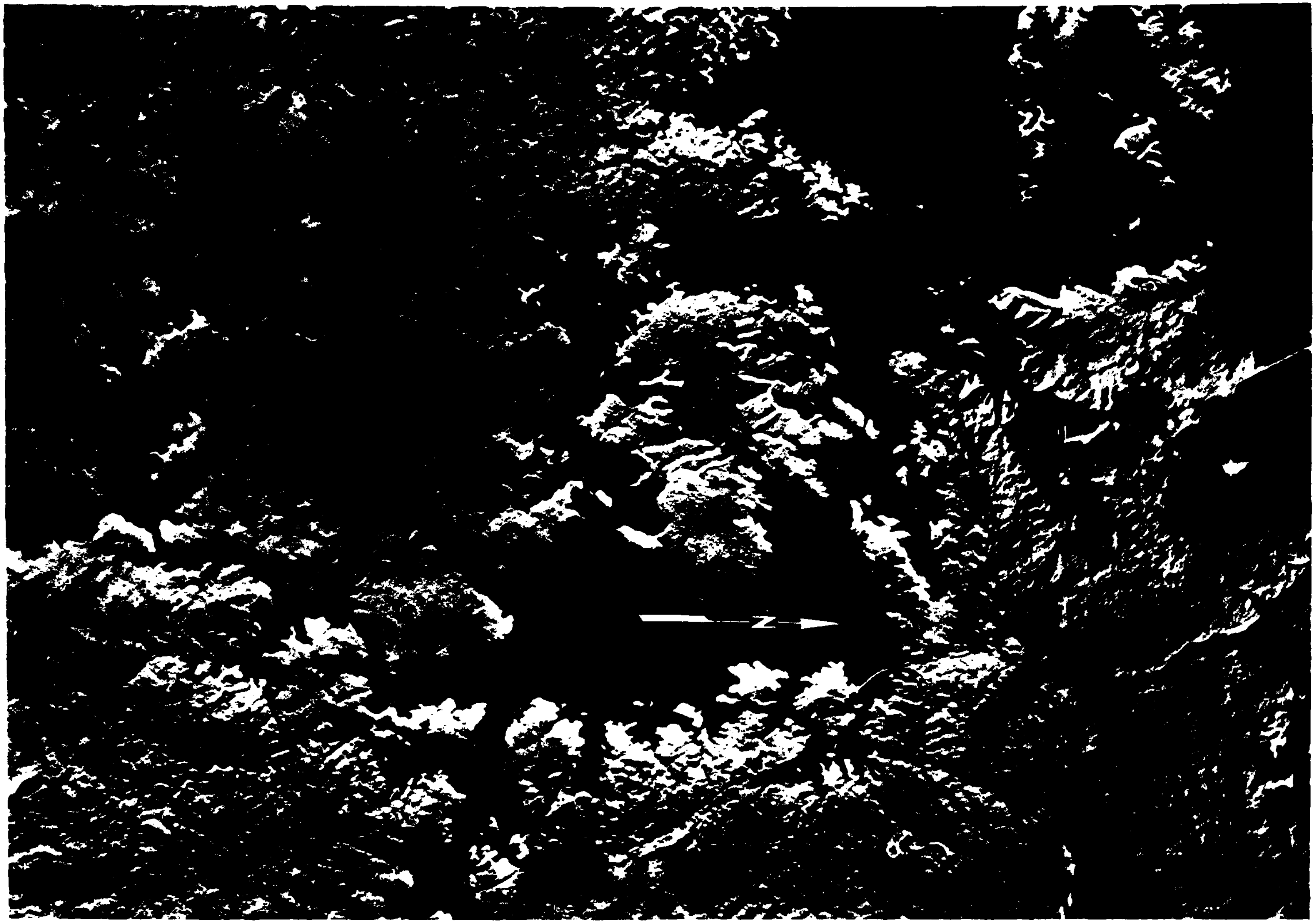


Figure 16. Radar with Drainage Overlay.

Figure 17. Radar Image of Barro Colorado Island with Lineals Overlay.

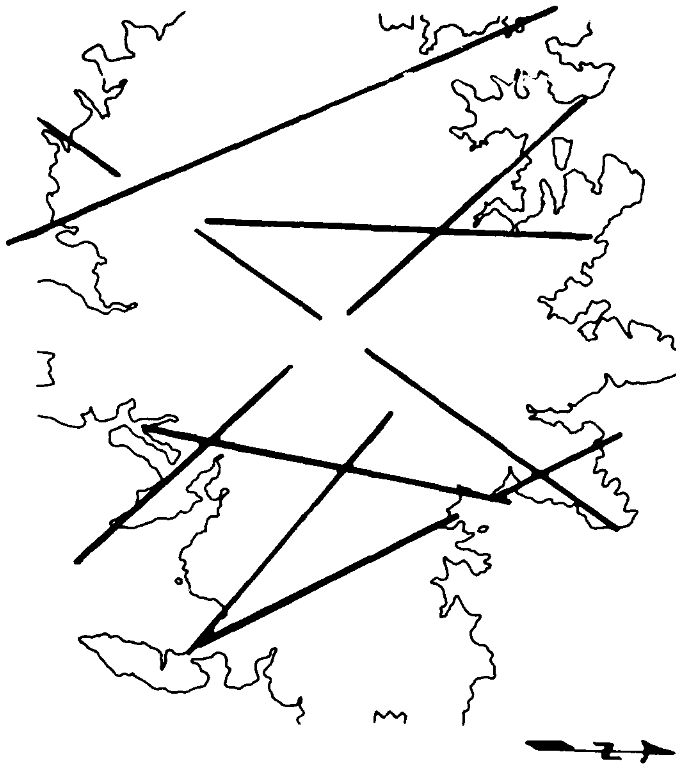


Figure 18. Lineals Common to the Aerial Photography and the Radar.

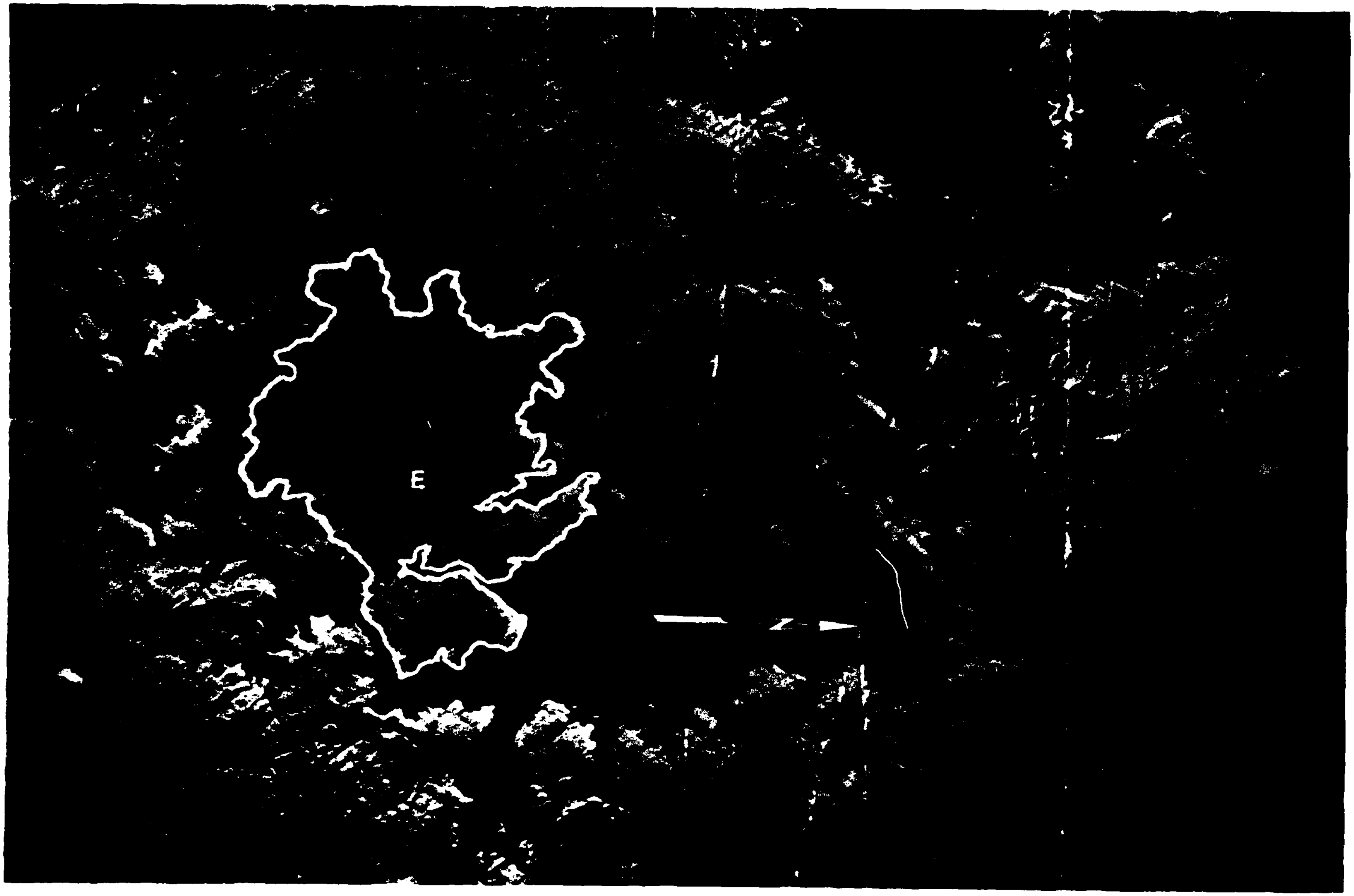


Figure 19. Radar and Vegetation-Caused Tone/Texture Boundaries. The tone/texture marked "E" in the 1972 radar image resembles that of Barro Colorado Island, which has a closed tree canopy. The highlight/shadow pattern around "E" corresponds to areas that have had much of the tree cover removed, and more of the ground topography can be depicted in the radar image.

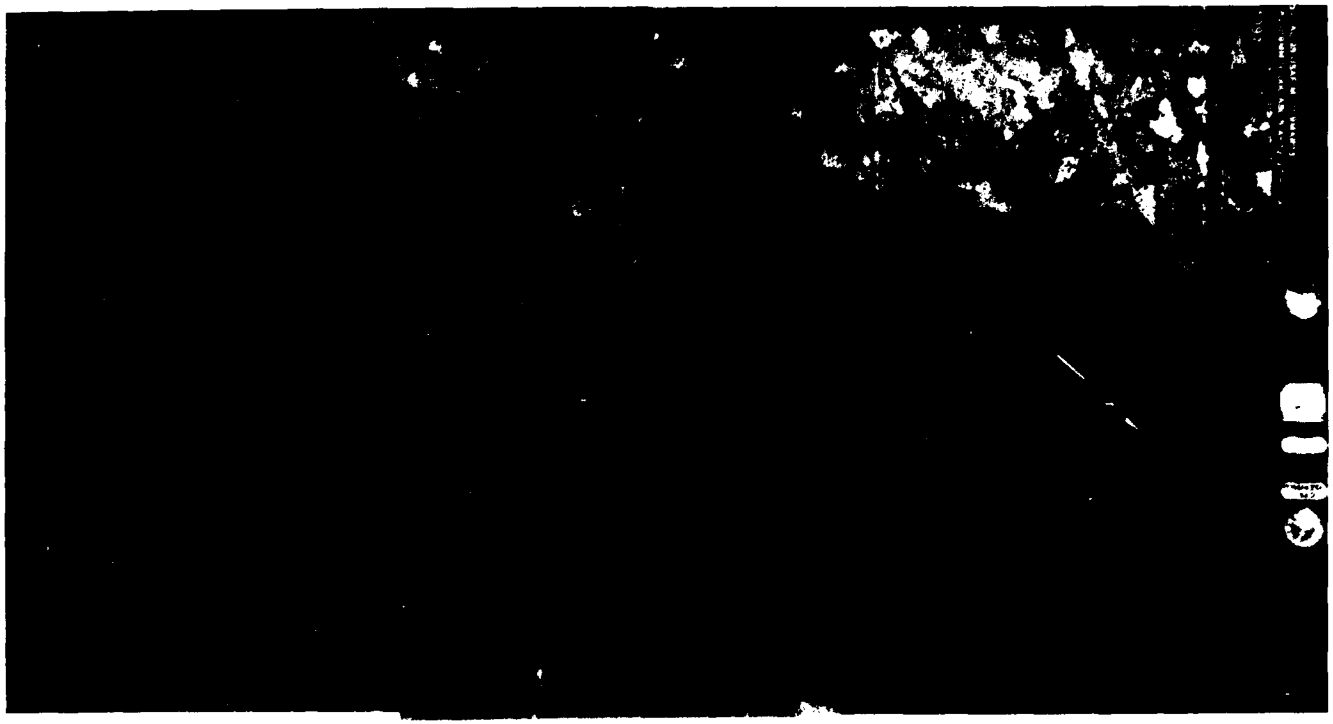
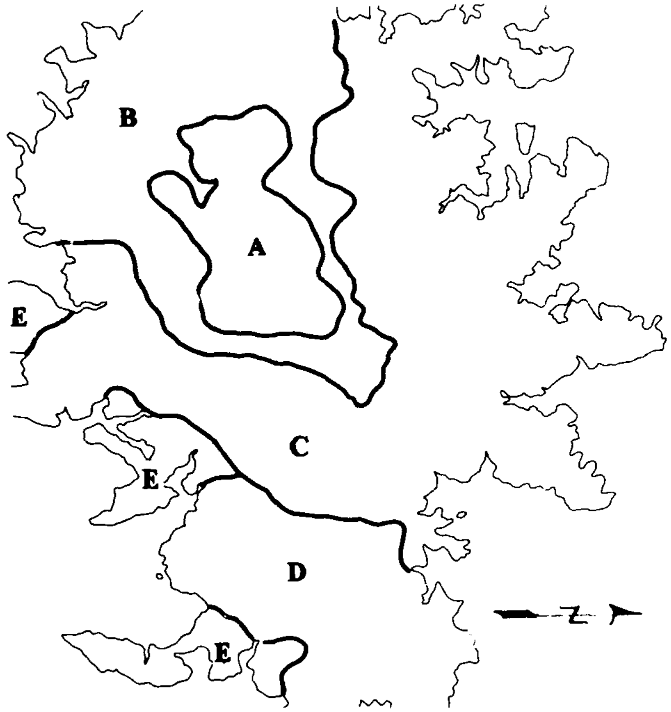


Figure 20. Air Photos and Closed Tree Canopy Boundary (1973). Above air photos of the area marked "E" on the 1972 radar image in figure 19 show that, at least in 1973, it was tree covered, and that the area around has been cleared of trees. The photos are USAF M-11, 1097 and 1099, 9 March 1973, 1:20,000 scale. The scale of this illustration is about 1:48,000.

Figure 21. Landsat Scene and Closed Tree Canopy Boundaries. A black and white copy of the Landsat color composite (bands 4,5,7) of the Barro Colorado area. The illustration is oriented in direction to agree with the radar image in figure 19, i.e.,north is to the right. The dark-toned area south of Barro Colorado corresponds in shape to the radar pattern outlined in figure 19, and to the same area in the air photos in figure 20. One can conclude then that area "E" was still tree covered in 1979, the date of the Landsat scene.
Landsat MSS 4,5,7 Scene E-21459-14465, 20 January 1979, approximate scale 1:250,000.



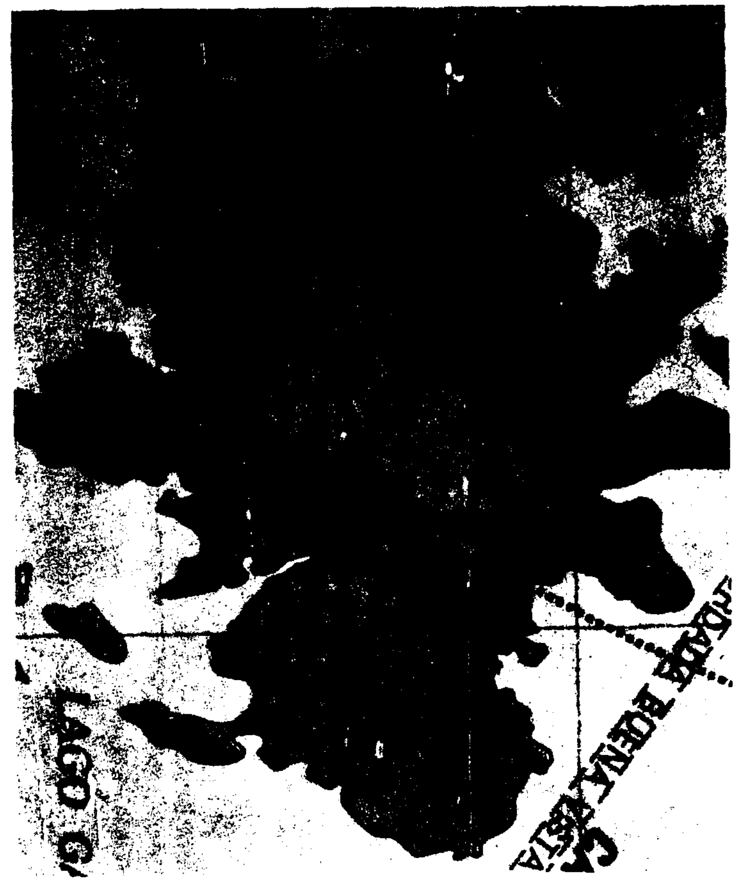


Figure 22. USGS Geologic Map of Barro Colorado Island. Copy of the Barro Colorado area of the USGS *Geologic Map of the Panama Canal and Vicinity*, compiled by R.H. Stewart, J.L. Stewart, and W.P. Woodring. The illustration to the left also shows the air photo-derived landform boundaries. The symbols in the USGS map are explained in table 2.

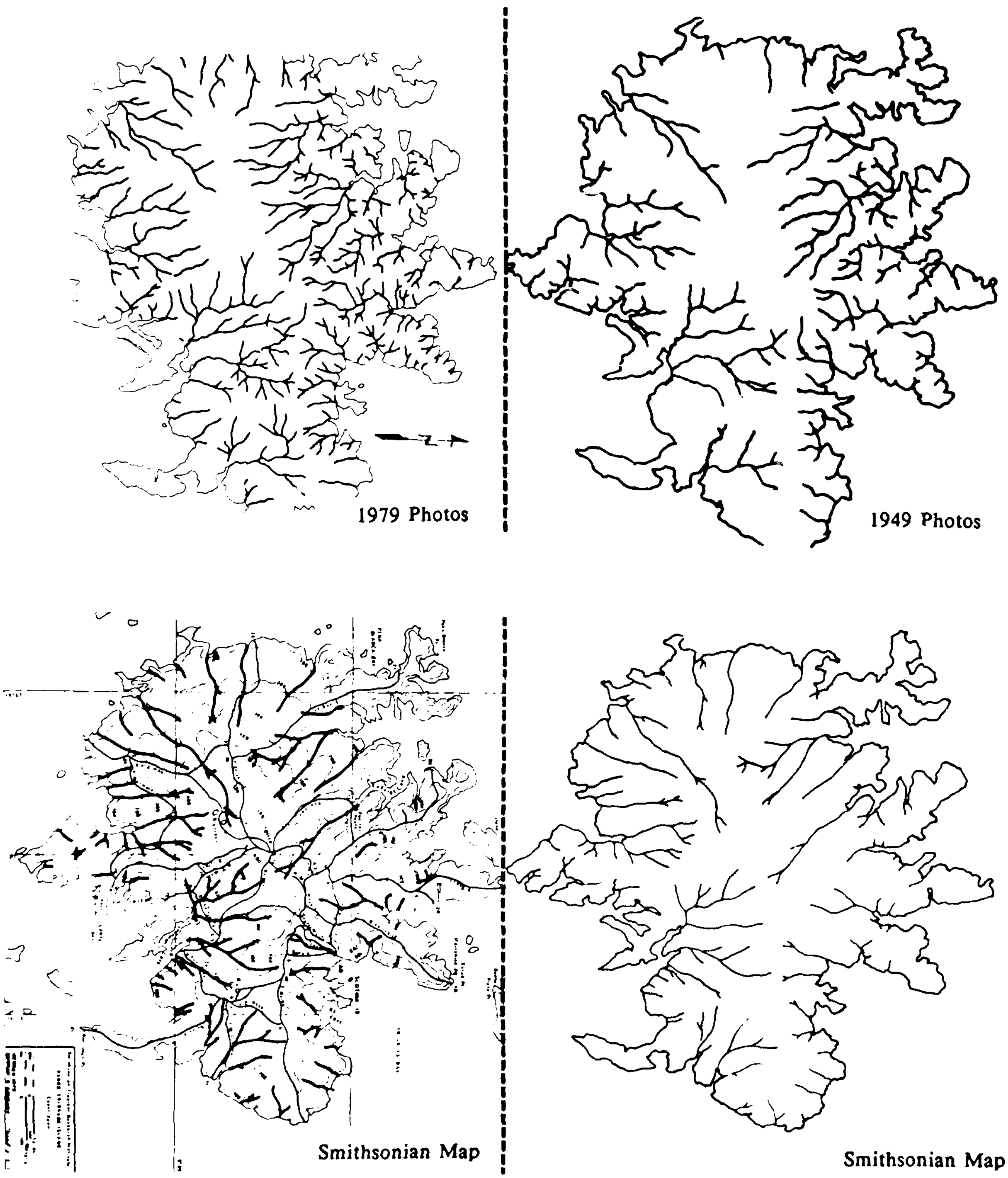


Figure 23. Drainage from 1979 and 1949 Photography and 1978 Smithsonian Map. Comparison of photo-derived drainage patterns and the Smithsonian map. The thin drainage lines on the map were emphasized with a heavier line, and also printed as a separate overlay.

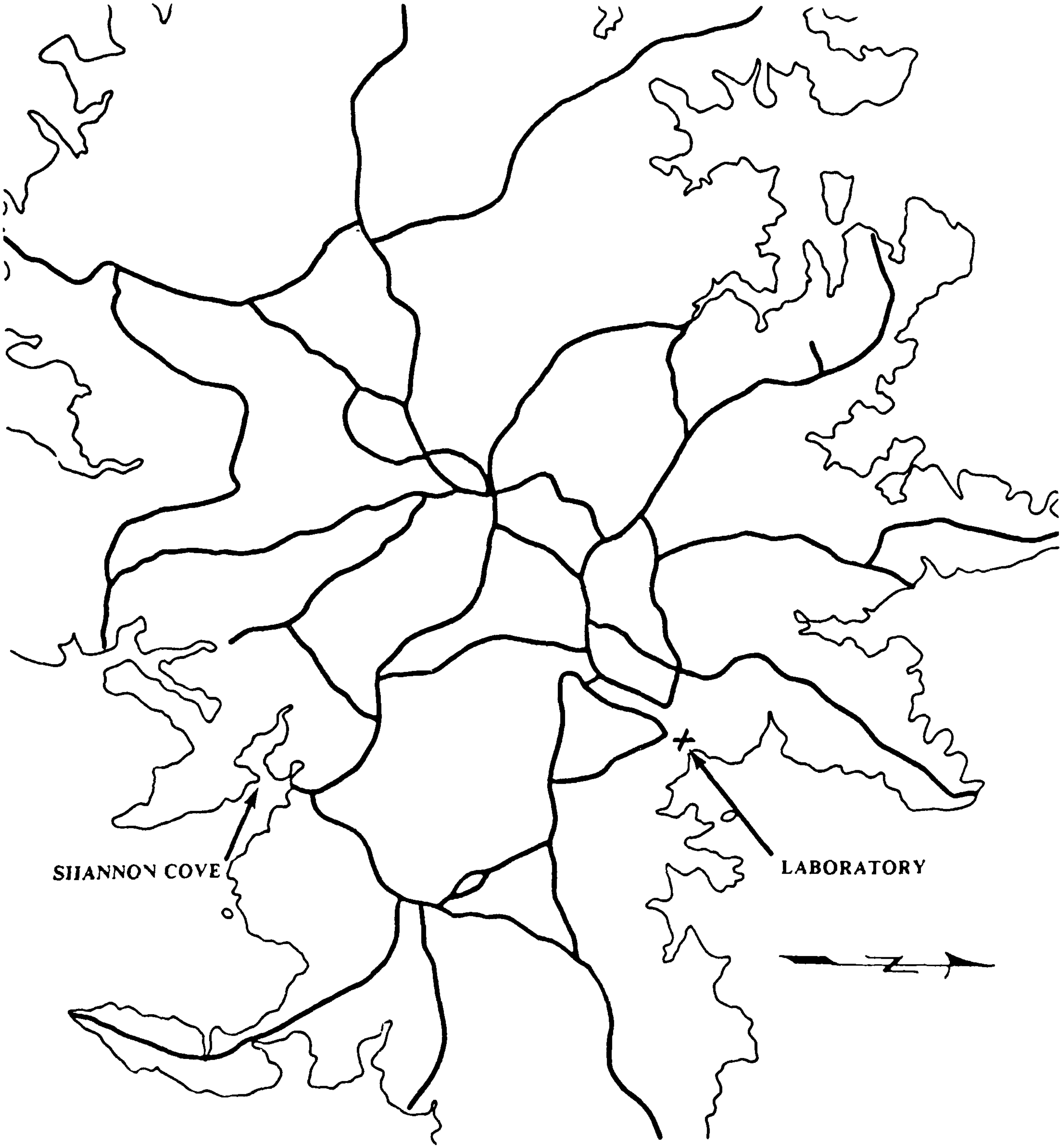


Figure 24. Barro Colorado Island Trail Overlay.

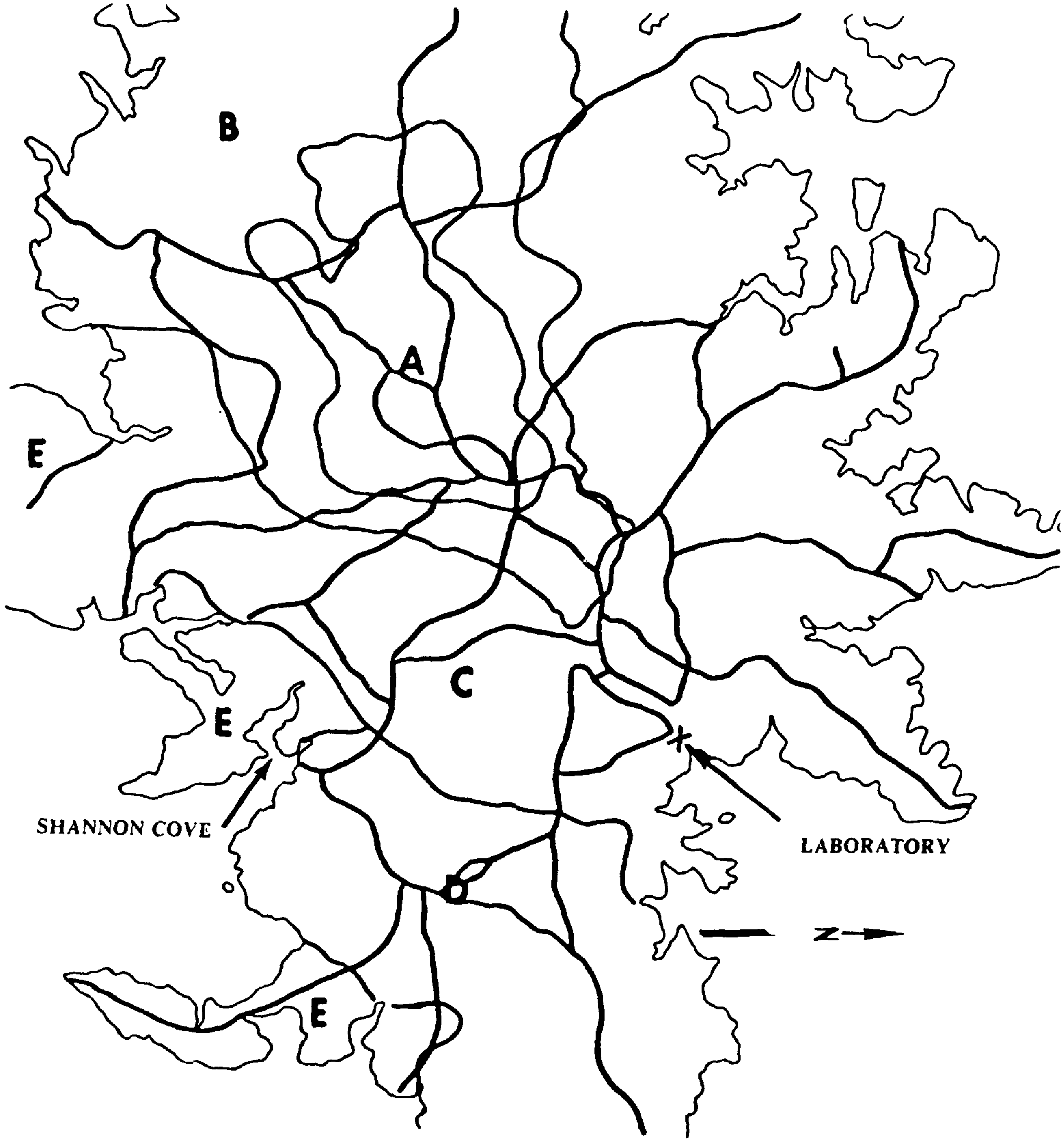


Figure 25. Barro Colorado Island. Trail Net With Landform Boundaries.

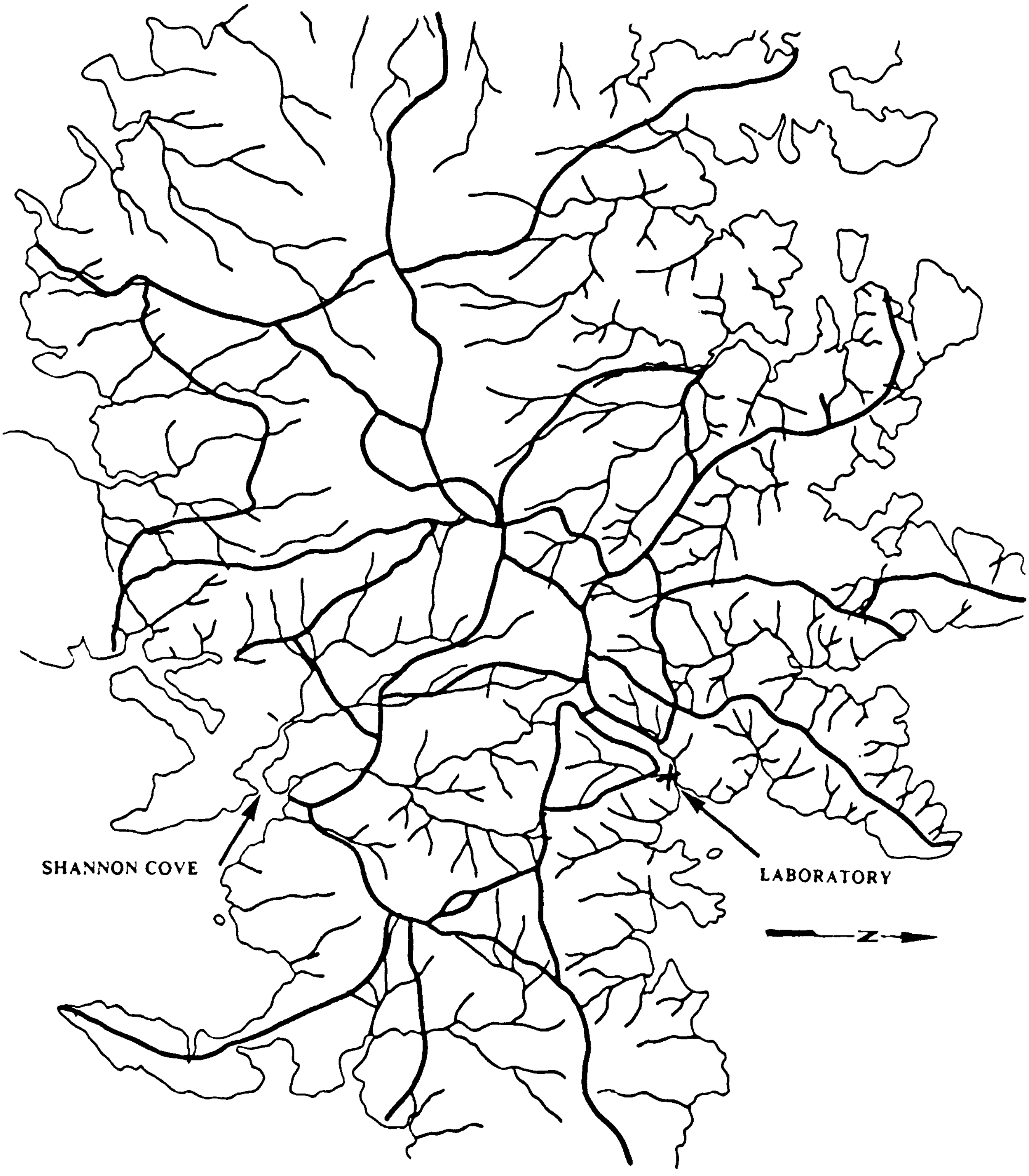


Figure 26. Barro Colorado Island. Trail Net with Drainage Pattern.

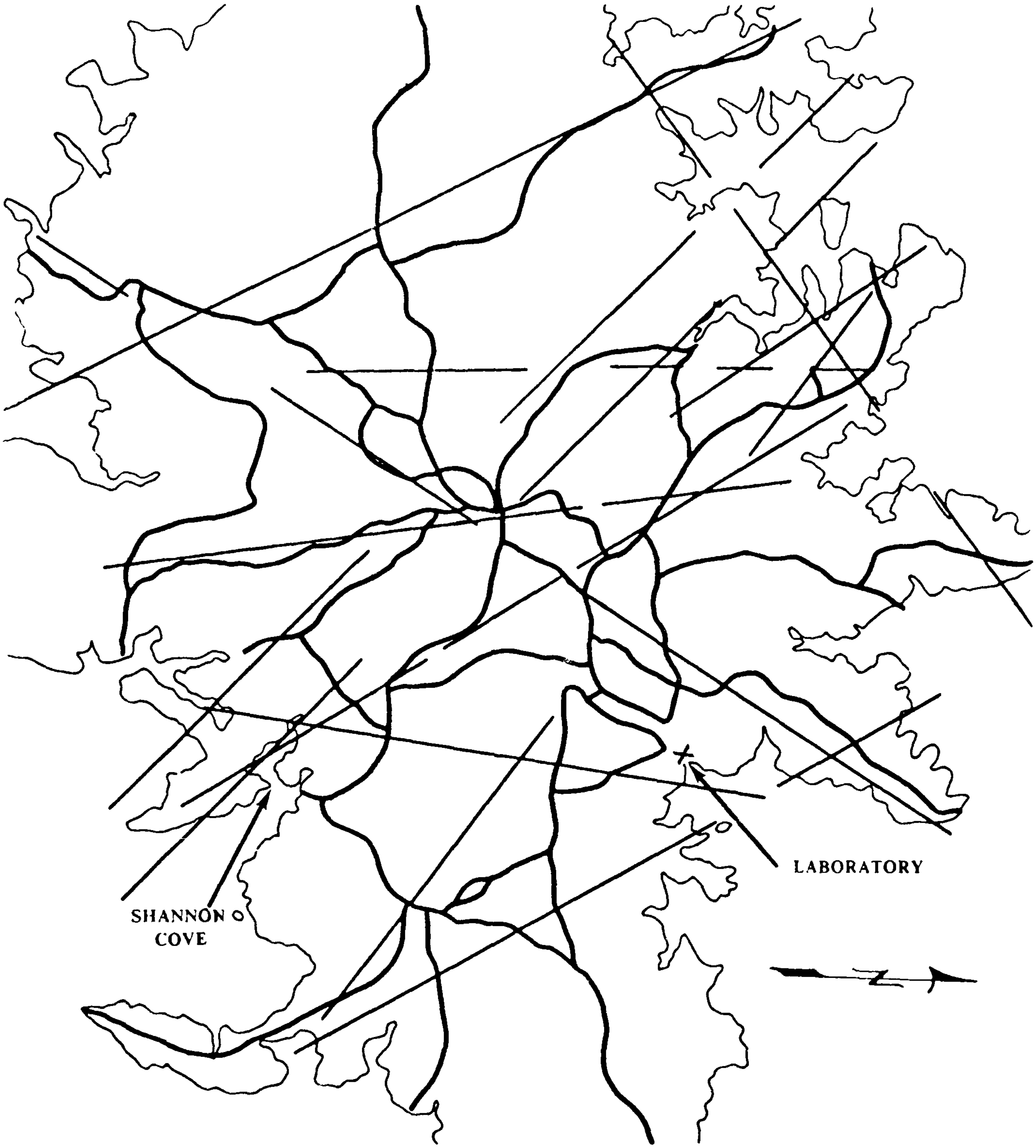


Figure 27. Barro Colorado Island. Trail Net with Lineals.